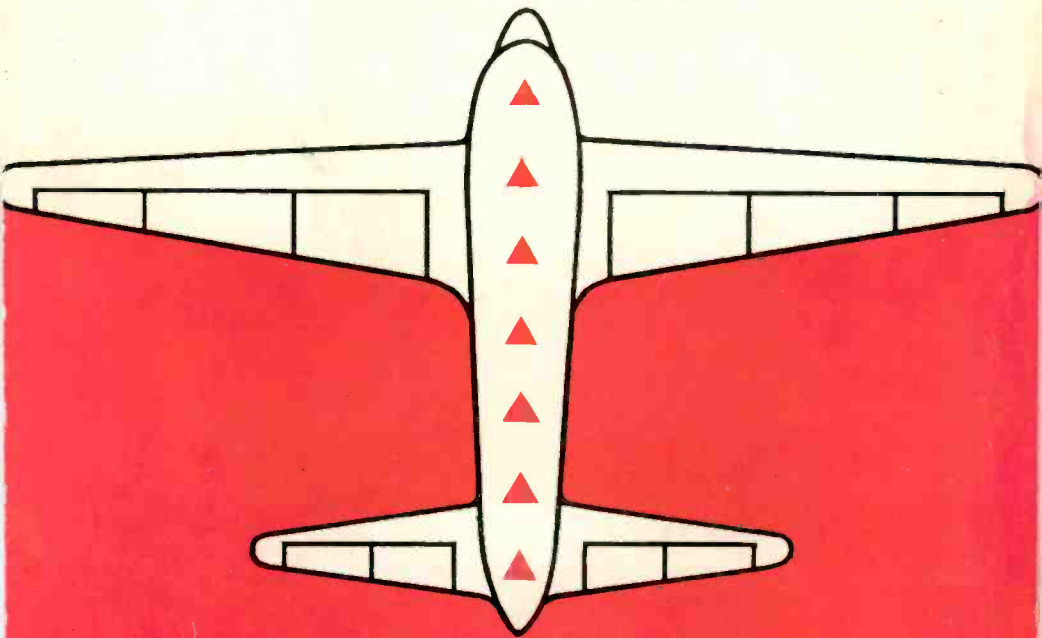


# Advanced Radio Control



- **Pulse decoders**
- **The control problem**
- **Frequency decoders**
- **Fundamentals of rockets**
- **Robots . . . facts and fancy**
- **Design and operation of proportional control servomechanisms**
- **Model rocket design and construction**
- **Superregen and superhet control receivers**

# **Advanced Radio Control**

**Edward L. Safford, Jr.**

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Advanced  
Radio  
Control



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# introduction

Many books have been written on the subject of radio control. Knowledge in this area has developed in leaps and bounds and, as we become more efficient in the standard methods, we begin to wonder if there can be any further challenge.

That is the reason for this book. It consists primarily of new thoughts (and some old ones) revised in an advanced light. It contains suggestions for new areas of endeavor, experimentation and challenge in this wonderful and exciting field.

The first chapter considers the advanced radio control problem. The following chapters take up the fundamentals of guidance, testing and instrumentation and the theory and design of amateur rockets.

Finally, that perennial subject, the robot, is considered and, to those who accept this challenging project, our heartfelt admiration, for this is indeed the most challenging of all control problems.

The author gratefully acknowledges the help and assistance of the following firms and agencies who have permitted the use of their material in this work: *American Modeler*, James G. Biddle Co., Burnell & Co., Debolt Engineering Co., *Electronics Magazine*, F & M Electronics Co., General Electric Co., *Grid Leaks*, *Model Airplane News*, *RADIO-ELECTRONICS Magazine*, Texas Instruments Co., Inc., Westinghouse Electric Corp. We also appreciate the assistance of the US Army Artillery and Guided Missile School, Fort Sill, Okla.; the US Army Air Defense School, Fort Bliss, Tex.; Helmut Bernhardt and our old friend Col. 'Bill' Sydnor.

We wish to thank the many readers in every field of electronics and modeling who have accorded such a warm reception to our previous works. We hope that this effort will also find your approval.

Finally I should like to thank Martha and Betty, my two sisters, who always find ways to help out.

El Paso, Tex.

E. L. SAFFORD, JR.

# the control problem chapter 1

The best way to arrive at a successful solution to the problem of radio and automatic control is to analyze every possible movement, action and operation to determine exactly what is to be done and what factors affect the ultimate performance. We must make the assumption that we are looking for perfection, and that we are willing to analyze and experiment to obtain it. While many concepts can be simplified if one resorts to advanced mathematics, we shall not do so here. Our approach shall be one which we hope will stimulate thought and provide a basis for experimentation so that the ultimate may be achieved.

## **The effect of delays**

When radio-controlling your airplane, boat or car, have you ever noted the time interval between sending commands and the time the model actually responded? Have you ever consciously thought how long that time interval is between the time when you yourself first determined that you wanted to send a command and the time you actually got the command sent?

Think for a moment. The model aircraft is overhead and you see that it is heading slightly off the course you desire. You analyze this situation for a second or two and then send a corrective command by pushing a button or moving a lever. There is definitely another second or two before you see the model correct its body orientation and then start moving in the desired direction.

If you send the command an instant too long, which is so often done, then the model corrects too far and you find it in error again. You send another command. The flight of the model becomes an oscillation

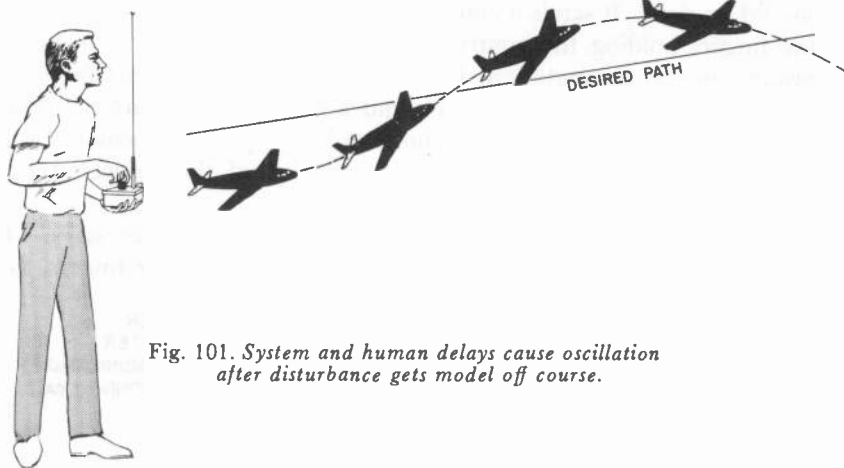


Fig. 101. System and human delays cause oscillation after disturbance gets model off course.

about the desired course, as shown in Fig. 101. We can say that the reason why this oscillation develops is the time delay or lag in response to our control system. Note that, when we speak of our control system here, we are including our own performance as well as the transmitter, coder, receiver, decoder, servomechanism (servo) and model.

### The basic control loop

The magnitude of this oscillation, caused by delay, is directly related to the speed and maneuverability of the aircraft. With a large, ultra-stable model, flying at low speeds, it is possible that the person controlling the airplane can, after some practice, learn to *anticipate* the model's response. Anticipation is the ability, when the model heads off course, to send a command that corrects the control settings so that the model does not overshoot or oscillate about the desired flight path.

This is the reason why expert fliers are able, with exactly the same kind of airplane, to outfly those with less experience or those who do not realize the need for this anticipation. There is always a breaking-in period with a new airplane as the controller or pilot learns how it reacts and how much he must anticipate before he can make it do precisely what he wants it to.

In Fig. 102-a we see a control system loop. We see, first of all, that the pilot observes the motion of the aircraft with his eyes. We call the control element which does this job a tracker. The tracker sends information to the brain as to the *speed*, *distance* and *angular orientation* of the aircraft, as well as its *heading*.

The brain (the *computer*) analyzes this information by comparing it with previous experience (memory), and then determines what



should be done. It sends a command, via the nerves, down the arm to the fingers holding the control stick. Note that there is an order of priority in the computation. It may well be that the *attitude* of the model must be straightened (to avoid a crash) before any positional change is effected. The original command for a positional change must then be modified in view of the new position of the model after its attitude has been corrected.

For example, let us assume that an attitude change is necessary. The brain flashes a command through the nerves down to the fingers, and

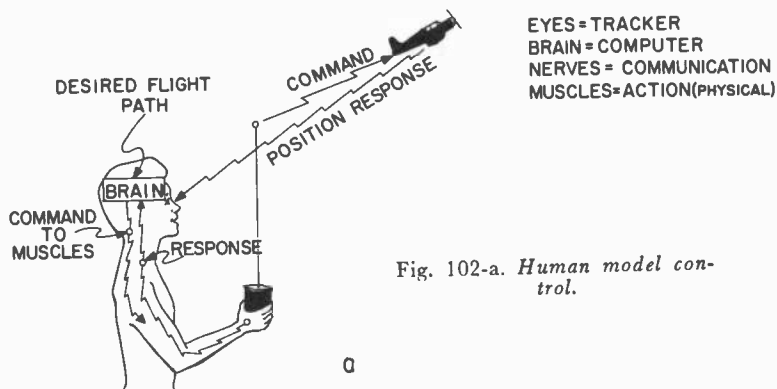


Fig. 102-a. Human model control.

the finger muscles push a button, move a lever or turn a dial, as the case may be. The brain knows that this operation is taking place, even without seeing it, because the nerves also carry information back to the brain regarding the pressure and feel of the control element against the finger tips. The brain *anticipates* about how much muscular reaction is necessary, and tells the fingers to stop when it thinks it has sent out the proper command. It doesn't stop there, however; it now uses the tracker's eyes for verification of its calculations. If the model's attitude isn't correct, immediately another command flashes to the fingers.

### The two loops involved

Let us examine the system more closely. First, the command generated in the transmitter must be sent out via radio to the model. The receiver must pick it up and route it to the proper control mechanism. This mechanism must move and, in doing so, move the control surfaces. The model itself will then respond, since the aerodynamic forces now acting on the model are different. The model first changes its angular position in space; then, because of this change, moves in a new direction. It is possible to present the picture of the complete control situation, as shown in Fig. 102-b, as a servomechanism with *two feed-back* loops. Note that the input to the system is what the human brain

wants the model to do. The large loop consists of the brain, servo, transmitter, model and tracker. The small inner loop is the muscular movement of the arm and fingers and the nerve feedback to the brain. In servomechanisms, delays can cause all kinds of trouble and malfunctioning, and here we have one servomechanism loop operating inside another.

### More delays

Two other delays then, assuming that transmission and reception of the command are instantaneous, are the time required for the control mechanism (in the model) to move and for the aircraft to respond. Now let's add them all up. There are the delays in the person while the brain works and the muscles move, and there are the two delays

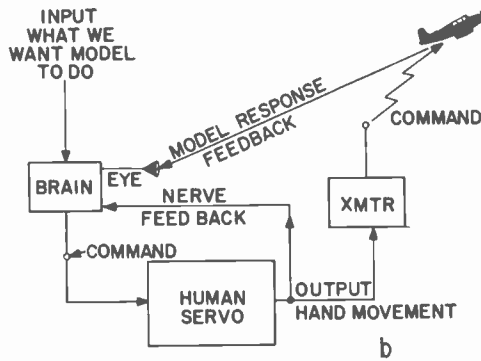


Fig. 102-b. Servo diagram. Internal and external feedback are required.

in regard to the model itself and its servo. Is it any wonder we generally lag a little when we try to control a reasonably fast aircraft? And is it any wonder that identical aircraft, with identical control systems, give different performances when different individuals control them? Brain and muscle responses can differ largely and the effect can mean the winning of a contest.

In a servomechanism, each part is tailored for a specific performance in a specific system. However, one cannot easily modify his own (human) servomechanism. For best over-all performance, then, one must tailor the control system and aircraft to fit one's human servomechanism. This might mean some modification of the models themselves; it might mean a different type of control system than a friend uses. Primarily, it means you should experiment to arrive at the ulti-

mate, the best, for your individual case. This is the reason why the experts who take home the trophies modify or adapt standard equipment or build their own.

### **Improving the human servo**

Delays, when they are large, can put a model into oscillation. A simple experiment will prove the point. Take a pendulum (which can be likened to the controlled body), swing it and, watching carefully, tap it at such a time and position that you make it stop swinging.

This is easy if the pendulum is long and the swing slow. Make the pendulum shorter and the difficulty increases. The swing becomes faster the shorter the pendulum gets. You may find that you will tap it at such a time and in such a direction that you help the swing rather than stop it.

In aircraft, this analogy applies to large and stable models versus small, fast, highly responsive types. What does this prove? It means that we should get faster responses from every part of the big servo loop. We must have very fast responses from equipment, and we must improve ourselves by practice.

### **The probability of success**

Let us now examine the control system's *reliability*. Reliability is defined here as the percent chance that any unit, or the complete control system, will operate properly during any particular flight or control operation. If a system is 100% reliable, everything should function correctly each time we fly. There will never be any bugs; we will always get the correct response to every command, and each command will be exactly the one wanted for that situation.

In computing reliability, the number 1 stands for 100%, 0.5 for 50%, 0.1 for 10%. A number like 0.5 means we have a 50-50 chance that everything will operate as it should. Normally, the figure should be larger than that. A good figure to shoot at, considering human errors too, would be 0.8 or higher.

Another interpretation can be made if the reliability figure is 0.5 (50%). One half the flights of the model will be perfect and the other half will have malfunctioning of equipment, model or pilot. Note that the word "malfunctioning" does not necessarily mean a crash.

How do we calculate the probability of successful radio control operations? We merely assign a reliability number, a decimal fraction, to each part of the system, and multiply them all together. Let's try an example.

Assume that you know the motor of the airplane will run as it should 90% of the time. We assign it the number 0.9. Assume that

the model will fly as it should 90% of the time (0.9). Also assign the 90% factor to the receiver, transmitter and servo individually. This is shown in the block diagram of Fig. 103.

The over-all probability of success, then, is the product of all decimal fractions:

$$\text{Motor} \quad \text{Airplane} \quad \text{Receiver} \quad \text{Transmitter} \quad \text{Servo}$$

$$0.9 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.59049$$

This means that we have about a 59% chance of success every time we go out to fly and radio-control our model (0.59 × 100). Is it any wonder then that sometimes we do have failures?

We can analyze each part of our system in terms of how successfully it operates and try to get each part as nearly 100% reliable as possible. With the control system, for example, we might send 1,000 commands

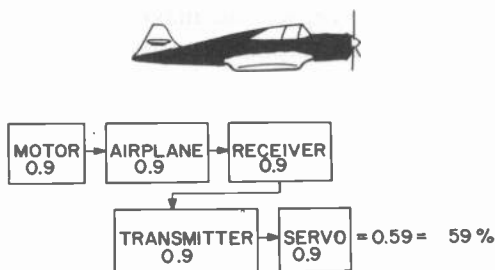


Fig. 103. In reliability, major parts of radio control include model. Reliability factor is product of terms.

at the average range of operation and see how many are executed correctly. (This is a kind of range test.) We say 1,000 because the more commands we send to take our sample from, the more accurate our individual reliability figures will be. The reliability factor then is:

$$\frac{\text{Number of commands correctly performed}}{\text{Total number of commands sent}}$$

If this figure, obtained by the calculation above, is low, then we should work to improve our system before putting it into operation in the model. Note that we have not shown a method of actually calculating human reliability. We will let you estimate how accurately you think you observe and how often you send the right command, at the correct instant, out of 1,000 operations while a model is in flight. Is your rating high? Whatever it is, be sure to include it in the final computation of the *over-all* system reliability.

## Improving the probability

How do we improve our chances of success? First, we must have a model, properly designed (as most manufactured models are), and second we must build it exactly as the manufacturers have specified. When changes are made, we must know what we are doing. Manufacturers have spent countless months testing and checking their models to make them as foolproof and reliable as possible. Yet how often do we build carelessly, make modifications that add too much weight, balance incorrectly and use too small or too large motors or propellers? A big percentage of failures and a low reliability factor for the model itself can be attributed to these causes.

This seems in contradiction to a previous statement that we should tailor the model to ourselves. It isn't. We should take advantage of the high reliability in the design efforts of the manufacturer first; then, with accumulated experience, we can make such modifications as we feel are necessary. Build an airplane exactly as specified. Fly it until you know it like the palm of your hand; then make the changes, little by little, very carefully, so that it becomes tailored to you as an individual.

With the control equipment, we must again take care to read and understand the specifications which most manufacturers furnish. Do not exceed ratings or attempt adjustments which require equipment you do not have. Take advantage of the installation and checking procedures and make sure to use the equipment in the same environment as the one the manufacturers have tested and adjusted it for. Again, study your equipment until you feel that it is a part of you, until you know its weaknesses. After that, never modify it unless it becomes absolutely necessary. A good rule here is: "When it's working right, keep your fingers out of it."

Reliability consciousness dictates that we must build equipment ruggedly and foolproof — not build with the idea of just wiring something together to make do. Always plan and build as though you expect to have your equipment held up as an example of a work of art, as though you expect it to last for many, many years without repair or adjustment. Take care in the selection of components, in soldering, in layout, in making good mechanical and electrical connections and in producing equipment that has a factory-like finish. You will then find your reliability factor nearing that 100% mark.

In the field of guided missiles, rockets and satellites, it was once thought that, since most of it is a one-shot object, equipment that would last for just one mission would be good enough. It has since been proved that, if a missile system is to be reliable for those few

minutes of operation, it must be built as though it were expected to operate for years! A friend once overheard an argument along these lines and, shaking his head he moaned, pointing to his model: "That means that it should be designed to last for centuries."

Practice will improve judgment and reaction time. With *human engineering* we can also improve the mechanics of the control system so they are best suited to an individual and there will be less margin for error. The physical shape, size and location of the controls should be tailored individually for optimum performance. Since there are physical as well as mental differences in people, a person who is large and muscular may have an inherent distaste for small, delicate knobs, levers and buttons. He may want controls he can grasp firmly, that require some strength to move and that feel good and solid.

Another person may want small levers, knobs, buttons and dials and, of course, everyone will have preferences as to whether the controls should be grouped together, separated, operated with one or both hands. There will be preferences as to whether the control box should be hand-held, mounted on a panel, held at waist level or shoulder height. The very type of control may make a difference. A radio amateur who is at home grasping the knob of a telegraph key may not feel at home pushing a button. His reactions may be slowed. Yet both devices do exactly the same thing—make or break an electrical circuit. So, again, to improve the human reliability, tailor the equipment to yourself. Determine the motions you are used to and determine the knobs and dials you can use most easily.

### **Control codes**

Much has been written about the general types of control systems; the single channel, in which compound servos or escapements enable you to have control over many functions and the more elaborate multi-channel types. Some of the multichannel types presently offer simultaneous and proportional control of sorts. Even the single channel types offer in pulse-width, pulse-spacing applications simultaneous control over rudder and elevator. With pulse-rate variations added, a third function can be controlled.

In this text we are primarily interested in *ideas* applicable to the simultaneous-proportional control problem. Let us begin with a consideration of coding, or methods of sending intelligence.

The following list covers the most obvious advantages and disadvantages of several methods:

#### **a. Combination pulse width and rate for control of two elements**

This has been successful in many applications. Its disadvantage is that it allows control over just two elements.

#### **b. Simultaneous transmission of two tones**

We say two tones because this is the normal number used without interference. We can control two elements with this system using any combination of tones as long as only two are transmitted simultaneously and as long as these two are well separated to prevent crosstalk or channel spillover.

#### **c. Simultaneous transmission of two varying tones**

Here discriminators are used in the receiving equipment to obtain proportional control. As of this writing, only single channel systems (in other words, one varying tone controlling one element) have been very successful. Transmission of two varying tones simultaneously would allow control of two elements.

#### **d. Pulse codes**

This type of system has not, to our knowledge, been investigated fully in the model field. While pulses would not be transmitted simultaneously, if their transmission spacing were very short compared to the response time of the equipment, they could be considered as a method of simultaneous control.

#### **e. Pulse position jitter**

This method, well-known in telemetry, is another application of pulse codes.

These methods can be sorted into two basic categories: pulses and tones.

### **Pulses vs tones**

To control a model with a proportional control system using tones, consider how many tones must be transmitted simultaneously, received and decoded. Since the control operations include motor, rudder, elevator and ailerons, a maximum of four tones at any one time are required.

Suppose we transmit a tone. Let's assume our transmitter is 100% modulated by this one tone. All the power in the carrier sidebands is due to this tone and when the signal is detected in the receiver, the tone amplitude depends on this sideband power.

If we send two tones simultaneously, then this sideband power must be divided. Less is now available for each tone. This means less power in each recovered tone. Three tones would allocate even less sideband power to each and four tones would have still less usable sideband power.

To be able to recover modulation with rather good decoding equipment there should be at least 12.5% modulation at the transmitter. This sets a maximum of eight tones to be transmitted simultaneously on any one carrier frequency.

We know the superregenerative receiver works best when it receives a 100% modulated signal. It produces its strongest tone output at this level. Since its detection curve is exponential, we can expect a sharp dropoff in recovered signal level with each additional tone to be transmitted. The output of the detector in a superheterodyne (superhet) receiver is also affected by the percentage of modulation of the transmitted signal but the linearity of the diode detector of a superhet is much better than the detector action of a superregenerative receiver. The superhet works better when simultaneous multi-tone modulation is used, especially when more than two tones are involved. The method of simultaneous modulation is also known as the *modulation-sharing* type.

### **Pulse modulation**

A transmitted pulse can be 100% modulation — it can occupy the whole carrier level if it keys the carrier pulse on and off. Think of pulses in terms of *trains* or *sequences* of pulses being transmitted at a very rapid rate. These can be used to get the same effect as simultaneous transmission without the disadvantage of low modulation as in the modulation-sharing situation. A pulse train could be 15 pulses of short duration, for instance, with a definite spacing between each of them, following a *marker pulse* — a pulse of longer duration to show the starting of each pulse train. The marker might also be a pulse at a different tone or frequency. Its sole purpose would be to reset a decoder in the receiver. Now we can send 15 commands — good, strong commands each using the full 100% modulation — and if we can transmit the whole train in a fraction of a second, the fact that they are sequenced will present no model-control delay problems. This method is called pulse-time modulation, the time sharing method, since each pulse occupies a part of the transmitter's ON time.

### **The decoding problem**

Perhaps the greatest difficulty in achieving multifunction, simultaneous and proportional control is in designing a suitable decoder to perform the function separation task for us at the receiver. The problem of combining many tones simultaneously or of generating pulses which can convey the necessary intelligence, is a minor one. We have no limitations as to the size, weight or space required for ground-based transmitting equipment. It can be complex and built to perform reliably. The real problem is in the decoder at the receiver, because we are concerned with size, weight, current drain and reliability. In the past, this problem has been almost insurmountable, but now, with



subminiature and microminiature parts, small, reliable decoders are feasible.

In every decoder there is some sort of switching device. This may be a relay, a diode or a transistor. For slow speed controls, adjusting the pull-in and drop-out operating points of the relay has been highly satisfactory.

However, when one deals in fast pulses (used in high-speed control), sparking, contact bounce and short contact time are troubles frequently encountered with relays. Sparking, for example, can produce signals similar to the pulses sent as control signals. Obviously we don't want this.

Let's look into this a little further. Throughout the control field we run into problems brought on by the mass of a moving object (such as a relay armature), the friction generated and other forces both acting on and generated by the object.

Mass has to do with the weight and density of a material. It is, in fact, the weight divided by the gravitational constant (32.2 ft/sec/sec). Mass gives rise to the concept of *inertia*. Inertia is that property of a body which tends to resist motion, but, when the body is in motion, it tends to make the body keep moving. An automobile has mass. Try to push it and you find it resists being moved. Get it rolling and you have trouble making it stop. Of course, there is friction involved due to the tires pressing against the pavement and the weight on the axles.

Now consider an armature of a relay. It also has mass, and therefore inertia. Spring tension and a magnetic field (when energized) oppose each other and cause the armature to move. Friction is involved. Put all these together and what do we have? First, consider the relay de-energized. Suddenly the circuit is closed, applying the magnetic field. The armature is set in motion. It doesn't want to move, because of its mass; the spring doesn't want it to move either, but the magnetic field, being stronger, makes it move. Once it is moving, the armature doesn't want to stop. It hits a solid contact and bounces. The controlled circuit is broken and then made again as the armature is pulled back by the magnetic field. Then, when the control circuit (magnetic field circuit) is broken, the spring pulls the armature back.

If everything is properly designed, and by this we mean the mass of the armature, the strength of the spring, the strength of the magnetic field, the friction of the bearings and, if the contacts are designed to give a little during the first impact, the armature will bounce without actually breaking the circuit. The relay, then, has been designed with the proper balance between mass, friction and the forces involved.

There is also air resistance to the armature motion, which we have not considered here, nor have we considered the pull of gravity on the armature.

As you can see, (in the decoding problem where high-speed switching is required), if relays are used, they must be carefully designed.

Decoding problems become more complex as we improve our capability to control, and we are fortunate that smaller components are becoming more readily available to accomplish the task. New horizons open up when we investigate electronic decoding.

### Mass--friction--forces on an aircraft

Now that we have introduced the concepts of mass, friction and force in connection with a relay, let us look for a moment at the aircraft. It, too, has these phenomena.

Fig. 104 shows a profile of a typical model. Everything is measured with reference to its center of gravity or balance point. We are concerned with the motion of the tail assembly when some disturbing air, say from below, momentarily whips the tail up higher than it

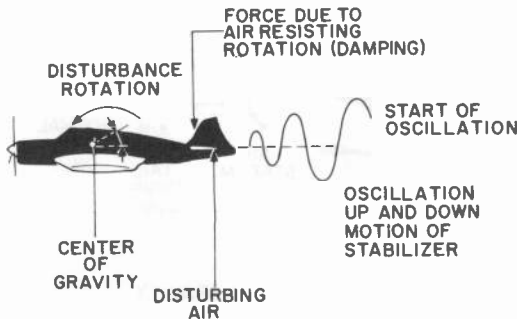


Fig. 104. Model mass tends to resist motion, but when motion is started, mass wants to keep moving, resulting in oscillation.

would be in normal flight. Note the direction of body rotation about the center of gravity due to this disturbing air (force).

Again we are concerned with mass and inertia. The aircraft tends to resist the motion, but once moving tends to continue. We are concerned with friction, the resistance of the air to the tail surface moving up (this is a damping effect), and we are concerned with the restoring force, the force on the tail due to the airstream from the propeller hitting the tail at an angle.

The graph of the stabilizer position shows that it oscillates up and down, but a smaller and smaller amount each time, until the tail

settles into its normal flight position. The physical part of the aircraft which made this oscillation die down quickly is the surface area of the stabilizer which directly determines the damping force. Thus we can see that an aircraft with a small stabilizer area might tend to oscillate longer than one which has a larger area.

There is another way in which this oscillation may be damped and that is with the control system. First let us assume that we have an aircraft with a medium-size tail surface and that we send it an up signal, using an escapement or a servo, which whips the elevator to the up position hard and fast. Let us assume that when the higher altitude is reached, we release the signal and let the aircraft level off.

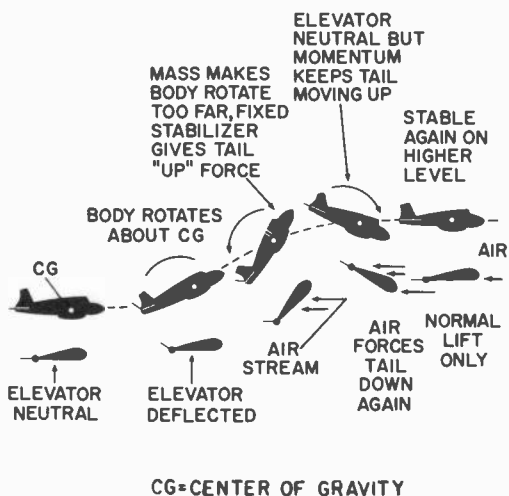


Fig. 105. Response of aircraft to "bang bang" elevator signal.

The picture is shown in Fig. 105. Notice that the quick deflection of the elevator is similar to the disturbing air of our previous case. The body quickly changes its angular orientation in space, and actually turns too far. When the elevator is released to neutral, the high angle of attack of the stabilizer, due to the body turning, produces a tremendous restoring force which whips the tail high. Then we have oscillation until the natural weathercocking of the model stabilizes it at the higher altitude.

One term in the equation is affected by our control system when we have damping built into the system. In this case, the damping is a

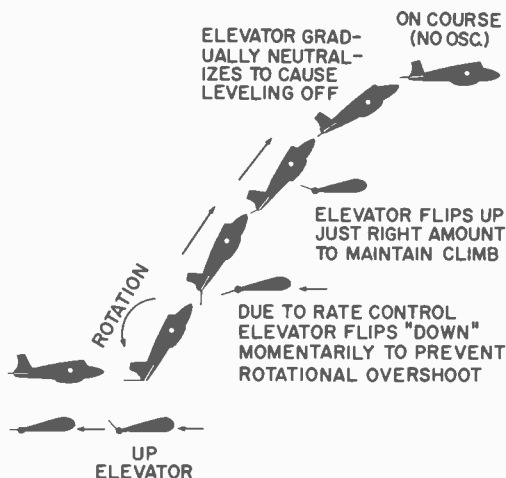


Fig. 106. Gradual deflection of elevator will prevent oscillation.

control signal which can be sent at the right time calling for the right amount of elevator deflection to prevent this oscillation. Fig. 106 illustrates this case.

In Fig. 106 we see that again we deflect the elevator for UP. This time, however, we have deflected the elevator just the right amount for UP, using a proportional control system. The body rotates as before, but now instead of overshooting the vertical climb line, note that when the correct climb angle is reached, the elevator deflects in the *opposite* direction to prevent further rotation.

The amount that the elevator deflected in the down direction would have been directly dependent on how fast the body was rotating (angular velocity). For a very slow rotation, the elevator might not deflect down at all, while for a very fast rotation, it would deflect a large amount.

Again, at the new altitude the elevator gradually neutralizes to level off, or if a fast leveling off is required, it would deflect first into the down and then the up position. This is the way autopilots in large aircraft work. That is why these aircraft fly so smoothly.

The question is — can we incorporate rate control, as this type of control is called, in model aircraft? We do insert a kind of rate control when we anticipate a model's maneuvering in normal flying. Perhaps we should consider the use of a rate signal (generated in the model servomechanism) to get smooth, proportional rudder, elevator or aileron deflections and get them quickly. This type control would improve any contest-airplane system and would insure control over very fast flying models.

# superregen and superhet control receivers chapter 2

One way to increase reliability is to reduce the number of parts in a control system. The fewer parts we have, the less perfectly each has to operate to achieve a given figure of success. For example, two parts each with a 0.9 reliability gives 0.81 or 81% for the system. Four

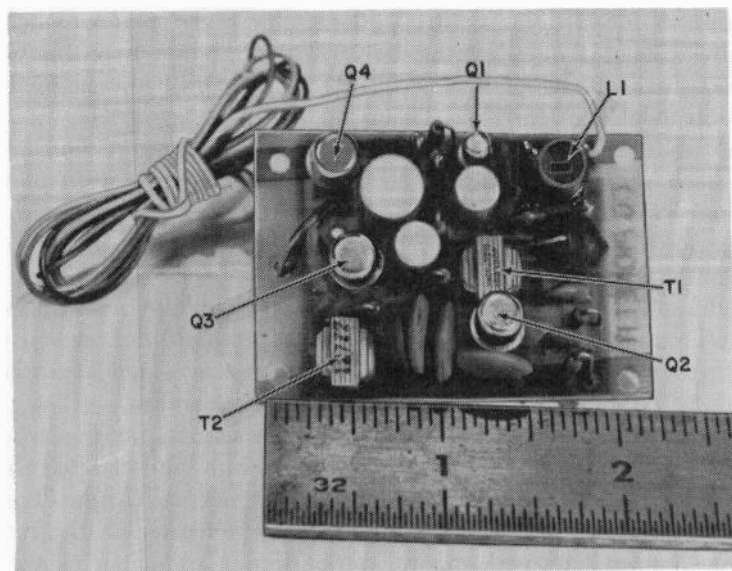


Fig. 201. Top view of superregenerative receiver. Set uses transistors only. Circuit is shown on page 22.

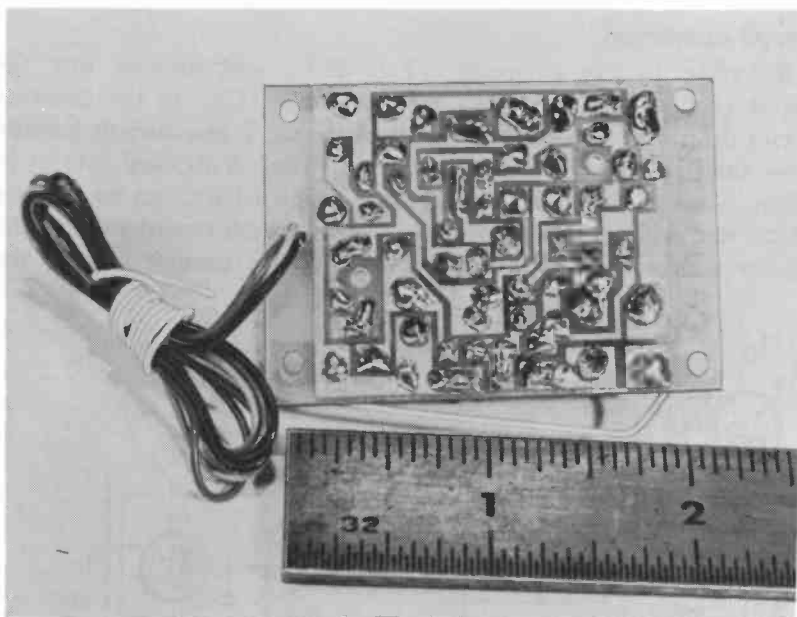


Fig. 202. Use of printed circuits reduces amount of wiring to be done.

parts with the same individual reliability would give  $0.9 \times 0.9 \times 0.9 \times 0.9 = 0.656$ , or about 66% chance of success.

In this chapter we will discuss the relayless and the superhet control receivers. The first is an example of reduction of parts—no relay. The second has many parts but each part has a reliability factor of very nearly 100%. These are proven receivers, and both are tone-operated. We shall discuss their operation, effects of adjustment and some theoretical considerations.

### **The relayless superregenerative receiver**

Fig. 201 shows a picture of this receiver. Note the small relative size. Wiring is reduced through the use of printed circuits, as shown by Fig. 202. The circuit schematic is shown in Fig. 203. This receiver uses transistors for the superregen detector and audio stages. Another transistor is used in place of the relay normally found in the output of control receivers. The particular advantages of this unit is that it is quite immune to engine vibration and there are no relay contacts opening and closing to generate spark interference.

Since the transistor replacing the relay is tone-operated, there is additional immunity to noise pulses. When two flashlight cells are used to provide the 3 volts needed to operate the receiver, there is usually sufficient current capacity to operate the other control circuits in the model from the same source.

## Circuit operation

Referring to the schematic (Fig. 203), we examine first the circuit of Q1. The coil (L1) and capacitor (C2) in the collector circuit determine the frequency to be received. When current initially flows through these elements, the tuned circuit is shocked into oscillation. Some of this oscillatory signal is coupled back into the emitter circuit and regeneration takes place. Regeneration continues until the emitter current charges C5 to a voltage high enough to stop the

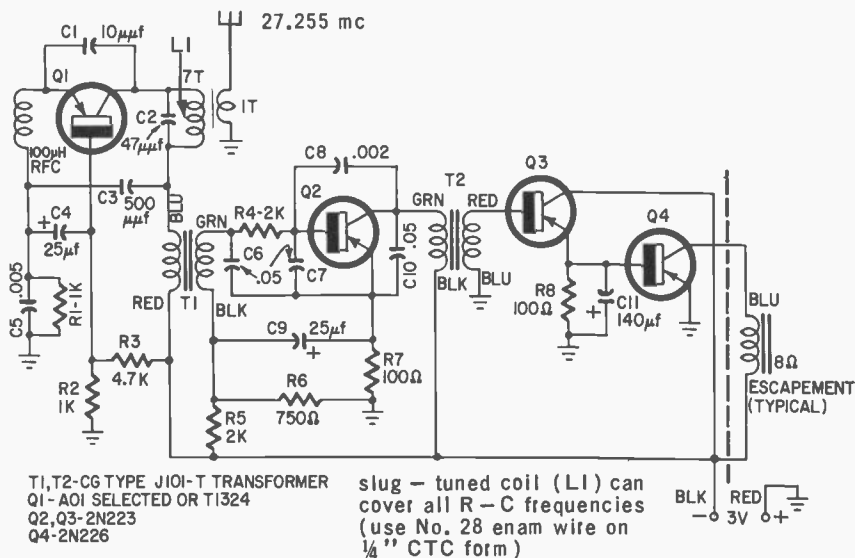


Fig. 203. Circuit of the superregenerative receiver. Relay normally used in output circuit, is replaced by tone-operated transistor. [Pioneer Receiver - C G Electronic Corp.]

oscillations. C5 then discharges through R1 and the whole action starts to build up again. C5 and R1 thus govern the *quench frequency* or the number of times per second that the detector stage oscillations are turned on and off.

As with most types of superregens, there is an energy burst sent out from this detector each time it is ON. These random bursts, when no signal is being received, result in the familiar hiss which we can hear in the earphones. When a signal is received, the bursts occur in a uniform manner related to the tone frequency, the hiss vanishes and we hear the tone. Note that while the signal is being fed back from collector to emitter during an oscillatory cycle, it is also being amplified. This type of detector can produce a signal amplification of up to a million times the signal strength received at the antenna.

The tone detected is then coupled through transformer T1 to transistor Q2. This second transistor is a temperature-stabilized audio amplifier which increases the signal level still further. C7 and C10 remove the quench or other radio frequency signals that might be present so that the tone is as nice and pure as we want it to be.

Transistors Q3 and Q4 are connected in cascade so that the current change through Q3 is amplified by Q4. At the base of Q4 we are no longer interested in the tone signal, but rather an average current which is developed from the tone. This base current can control the large current in its collector-emitter circuit to operate an escapement without the use of a relay.

The primary consideration, then, is that this receiver be simple and straightforward without moving parts. Its disadvantage lies in the type of detector itself. This detector is inherently broadly tuned which means it can receive interfering signals if another tone transmitter is tuned close to its operating frequency. However, in some control applications, this broad tuning is a good feature in that the receiver will not detune and lose its control transmitter signal easily.

### **The superheterodyne receiver**

The small size of this receiver (Fig. 204) has been made possible by the development of the transistor and the other miniature com-

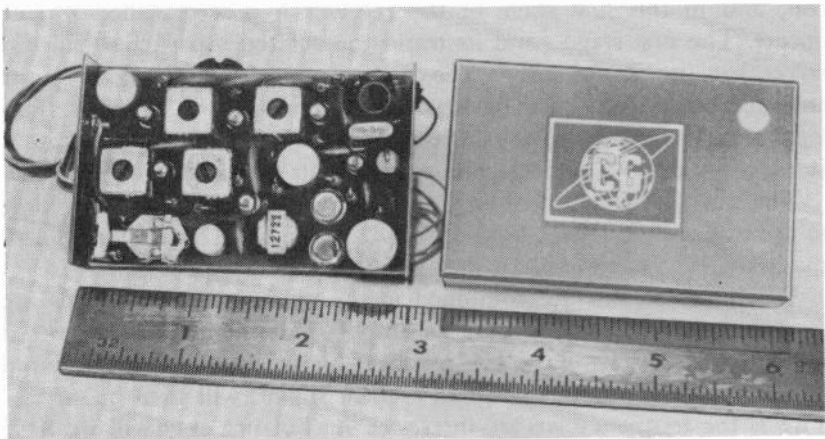


Fig. 204. Compact superheterodyne receiver uses miniature components. Circuit is shown on page 27.

ponents. It is little larger than the superregenerative receiver in Figs. 201 and 202 but with much better performance.

The way in which a superhet detects a radio signal and converts it into a sound which can be heard, assuming of course that a tone-



modulated signal is transmitted, is quite different from that of the superregen. The superhet's operation can be better understood by referring to Fig. 205.

It will reject interfering signals from transmitters tuned to frequencies very close to that of the transmitter from which it gets its control signals. This circuit will also deliver a much purer tone to the amplifier circuits because of the better linearity of its diode detector.

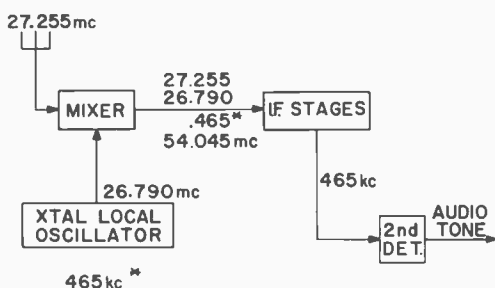


Fig. 205. Block diagram of superheterodyne.

Here a 27.255-mc signal is picked up by the antenna and tuning coil, and in this first stage of the receiver a process called *mixing* occurs. The first stage (and its transistor) of the superhet is called a *mixer* because it not only receives the transmitted signal from the antenna, but also a signal from what is called a *local oscillator*. This local oscillator is very similar to the oscillator used in the transmitter. It has a crystal to keep its signal set exactly to a certain frequency.

The purpose of the local oscillator is to generate a signal very close to the transmitted signal. Note in Fig. 205 that its frequency is 26.790 mc, only 465 kc lower than that picked up by the antenna.

When two signals are combined in the mixer two new signals are produced giving a total of four. To simplify matters, imagine, as shown in Fig. 206, that we have a 4 cps local oscillator and that our input is  $3\frac{3}{4}$  cps. The difference signal, or beat signal, will then be  $\frac{3}{4}$  cps. This is the frequency we are interested in, but not only will we have the difference frequency, but a sum frequency as well, plus the original input and local oscillator frequencies. For the 27.255-mc receiver we will have:

- a.  $27.255 + 26.790$  mc (54.045 mc)
- b.  $27.255 - 26.790$  mc (0.465 mc, or 465 kc)
- c. 27.255 mc
- d. 26.790 mc

Each of these four signals will contain all the intelligence which was present in the original 27.255-mc signal. We are interested only in the 0.465-mc (465 kc) signal which is the difference between the antenna and local oscillator signal. This is the 465-kc intermediate frequency.

The i.f. signal is then separated from the others by sending all four through another tuned circuit. This circuit is tuned to the wanted 465 kc and, just as the antenna tuning coil rejects all signals to which it is not tuned, this circuit rejects all signals but the selected one of 465 kc.

To amplify this i.f. signal, several transistors and tuned circuits are required. The i.f. signal is then sent to a transistor or a diode detector

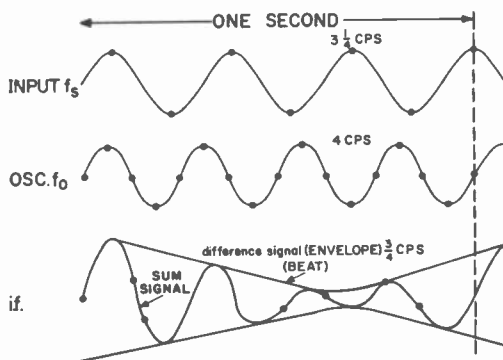


Fig. 206. Plot of result of mixing local oscillator and input signals. A low frequency was selected for clarity.

(which is also called a second detector since it now separates the tone from this lower radio frequency signal). The audio or tone amplifying circuits following the second detector are similar to those used in a superregenerative type control receiver which operates on tones.

### Superhet selectivity

First of all, note that the local oscillator frequency is controlled with a crystal. The only control signals with which it can combine to produce a difference frequency of 465 kc are 27.255 and 26.325 mc. The receiver antenna tuning circuit will reject the 26.325-mc image signal (if it is not too strong), leaving only the 27.255 mc signal.

The i.f. tuned circuits in this superhet are so designed that a signal which is only 2 kc higher or lower than 465 will be amplified only seven-tenths as much as the designed signal. The bandpass is defined

by this value of amplification and the bandwidth is said to be those frequencies amplified from maximum down to this 0.707 value. Note that signals which are 3 kc higher or lower than 465 kc (Fig. 207) are

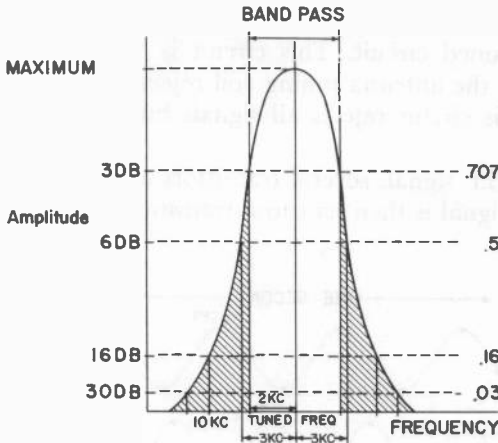


Fig. 207. Receiver selectivity curve.

amplified only half as much (0.5) and signals 10 kc off will be amplified only 1/6 (0.16) as much as the exact frequency.

The Q (figure of merit) of the i.f. transformers is the major factor that governs the bandpass (selectivity) of the receiver. The Q of the

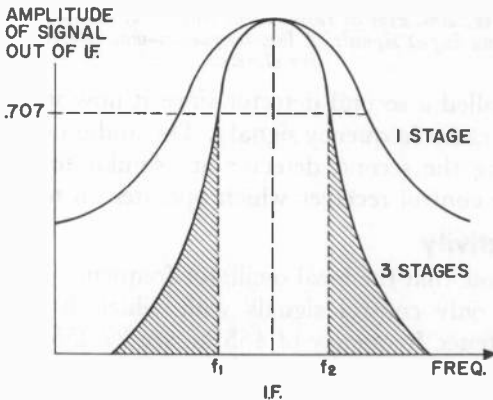


Fig. 208. Effect of a number of i.f. stages. The bandwidth is the frequency separation between the .707 points on the curve [f1 to f2 for the three-stage amplifier]. Note how much broader the single-stage bandpass would be.



transformers depends on the size and type of wire, core material and other mechanical and circuit variations.

The selectivity of the receiver is governed by the care in tuning the transformers, the method of coupling to them and the load the respective transistors put on their tuned circuit as well as the number of tuned circuits (transformers) in the i.f. amplifier.

Fig. 208 shows how the bandpass is broadened when only one i.f. stage is used compared to an amplifier of three stages.

The circuit schematic is in Fig. 209. Because of the amplification obtained in the i.f. amplifier only a transistor detector and relay stage are required for good reliable control operations. This receiver, like the preceding one, requires only 3 volts for operation. The detector (Q5) also amplifies.

The local oscillator frequency in a crystal-controlled receiver cannot be varied without changing its crystal and will receive one frequency only. It is possible to change the tuning of the i.f. transformers to receive a signal of a different frequency, or to tune the receiver to a transmitter which may have a crystal frequency a little different from that furnished by the manufacturer of the receiver. If the i.f. tuning is changed from, say, 465 to 475 kc, and the local oscillator frequency is not changed, then the incoming signal will be 27.265 mc instead of 27.255 mc.

The  $Q$  of the i.f. coils may change when they are adjusted to this new frequency. Using the curve of Fig. 208 we could say that when the i.f. amplifier is adjusted to its design frequency, its bandpass curve is similar to the curve shown for three stages. When the i.f. transformer is tuned to a nearby frequency, its  $Q$  may change; then the curve broadens as for one i.f. stage in this figure. Arbitrarily changing the i.f. frequency could result in reducing the receiver's ability to reject unwanted signals.

To get optimum efficiency you must peak each one exactly. If each stage is slightly off tune, then the bandpass broadens (Fig. 210) so that all signals between  $f_1$  and  $f_3$  are received. If all three are adjusted so that all curves coincide, not only does the gain increase, but the bandpass narrows down to amplify only those frequencies between  $f_1$  and  $f_2$ .

### **How are the i.f.'s tuned?**

A common method to align the i.f. amplifier would be to remove the crystal from its socket in the receiver, connect a signal generator to

the antenna terminals and set it exactly to 465 kc. A sensitive meter<sup>1</sup> could be connected across the load resistor (R11) for the second detector Q5, and each i.f. transformer, would then be adjusted, in turn, for a maximum indication on the meter, readjusting each i.f. transformer several times after the first attempt.

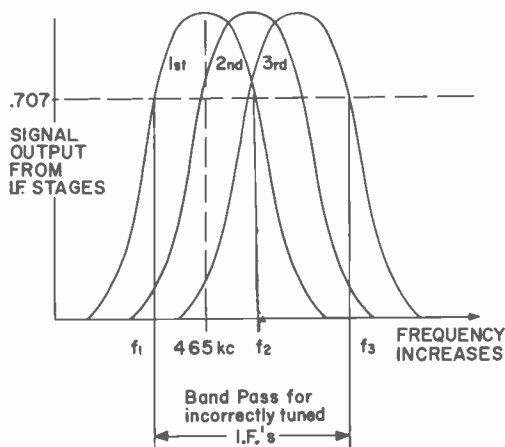


Fig. 210. When stages are stagger-tuned [all not tuned to same frequency] bandwidth goes [from  $f_1$ - $f_2$  to  $f_1$ - $f_3$ ]. This lets interference come through.

The manufacturer of this receiver does provide a method whereby, in a case of absolute necessity, you can adjust the i.f.'s in the field, using a matching frequency transmitter (one designed to operate the receiver) and a 100-ma dc (full-scale) milliammeter. The procedure is as follows:

1. Connect the meter in series with one of the battery leads. You should get a reading of 3 to 5 ma.
2. Key the transmitter. You should note a reading of about 35 ma.
3. Remove the antenna from the transmitter, hold the key down and have an assistant move the transmitter away until the reading drops to 15 ma. Now, holding the transmitter absolutely stationary at this distance, adjust the i.f. transformer slugs in their order (1, 2, 3, 4) for maximum meter readings.
4. Move the transmitter further away until the meter readings drop to 10 ma. Readjust the i.f.'s again in the same order for maximum reading.

<sup>1</sup> Use a vom [volt-ohm-milliammeter] or preferably a vtvm [vacuum-tube voltmeter]. Set the instrument function selector to read dc volts and the range selector at or near its maximum counter-clockwise position.

5. Repeat step 4, using extreme care to get the absolute maximum reading.

6. Place the cover on the receiver and, using a plastic tuning wand, tune the rf coil for maximum meter reading. The receiver must be connected to the antenna you plan to use during this last adjustment.

### Double conversion

There is a possibility that increased selectivity (or much higher frequencies than those presently allocated) will be needed for radio-control purposes.

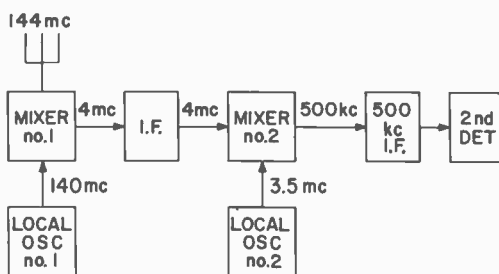


Fig. 211. Block diagram of double-conversion superheterodyne.

We have seen how a local oscillator signal can be combined with an incoming signal to produce an i.f. signal. Double conversion simply means that we repeat this process again. Note in Fig. 211 that two local oscillators are required. To make it easier, assume that the incoming signal is now at 144 mc. After the first mixing operation, the difference signal is 4 mc. Mixing again, after some amplification, with a local oscillator signal of 3.5 mc produces an i.f. of 500 kc which then can be amplified in a second series of i.f. stages and fed to a detector as before.

There is also need in the superhet circuit for automatic gain control (agc). This is an electronic adjustment of the amplitude of the output signal so that it always stays at about the same level. After the i.f. signal is detected, a part of this signal can be filtered to remove all variations in level due to the transmitted signal. This dc voltage then has a magnitude which is directly proportional to the strength of the carrier signal. If this voltage is fed back to the i.f. stages in such a way that the larger it is the less the i.f. stages amplify, we have automatic gain control. Strong signals will not be amplified as much as the weaker ones. This would allow operation of the receiver close to a

strong transmitter and also at a distance with the best possible performance. There would be less blocking due to circuit saturation from a too-strong signal.

Crystals, too, can be used in the i.f. stages to produce selectivity curves so sharp that signals more than a few cycles away will be rejected. Better selectivity is important when we want long distance control or fly many models at the same time.

It is also possible to narrow the bandpass of the i.f. stages of a receiver by having a regenerative i.f. stage. With some feedback of the i.f. signal, not enough to cause oscillation, the bandpass would become very narrow and much greater selectivity would be obtained.

The superhet is well adapted to the reception of pulse signals using the carrier alone. Just as we have indicated that the i.f. signal may be filtered and rectified and used for agc purposes, so too, it can be used to control the current of a subsequent transistor stage, like Q4 in Fig. 203. When carrier pulses are transmitted, the intermediate frequency will be in pulses, the current from the transistor stage following the detector will be in pulses and these could be large enough, or be amplified further, to operate a pulse decoder directly. We are going to discuss some uses of pulses later.



# frequency decoders

## chapter 3

The element of the control system following the receiver is the decoder. Our interest now lies in frequency decoders and their possible application to simultaneous and proportional control. Frequency decoders use tones (or variations of tones) to convey the control signals.

The reed type decoder has achieved great popularity among radio-control enthusiasts. This decoder is used to operate relays which, in turn, activate the various control mechanisms that use either no power or full power. We are going to assume that you are familiar with this operation and we will cover other possible applications of this unit.

### The problem

One basic problem in adapting the reed-type decoder (Fig. 301) to simultaneous-proportional control is the fact that it is essentially an

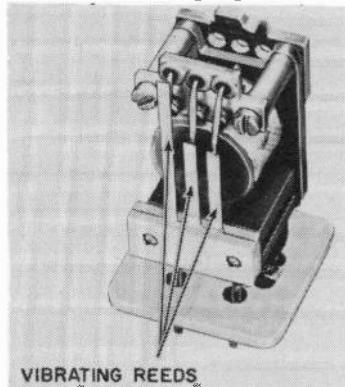


Fig. 301. *Triple reed decoder responds to three audio tones.*

OFF-ON device. When the reed vibrates it makes intermittent contact with a fixed point.

### Auxiliary relay

The intermittent reed contact is undesirable in most switching applications. An auxiliary relay is used to give a steady closed contact whenever that relay reed is vibrating.

An auxiliary-relay circuit for use with the reed relay is shown in Fig. 302. Here the auxiliary-relay coil is represented by an inductance

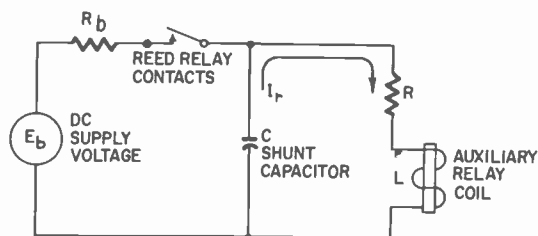


Fig. 302. Auxiliary relay circuit.

( $L$ ) in series with a resistance ( $R$ ). The capacitor ( $C$ ) connected across the coil is used to store energy during the closed period of the reed-relay contacts and then discharges this energy into the coil of the auxiliary relay during the reed open-contact period.

The reed-relay contacts operate at a frequency ( $f$ ) and are open for as much as 95% of each cycle so that the length of the open period is very nearly equal to  $1/f$ . The closed period is not less than  $120f$ . For intermittent duty at frequencies greater than 200 cps, the auxiliary relay coil may have a resistance of 5,000 ohms and require as much as 200 milliwatts to operate. The inductance of the relay coil should be around 12 henries, the supply voltage ( $E_b$ ) should be 3.5 times the maximum required to pull in the relay armature ( $E_b = 3.5 \times I_r R$ ) and  $C = .5 \mu f$ . Where operation is to be more frequent or where extra long life of reed contacts is desired more sensitive auxiliary relays must be used.

Fig. 303 shows a curve from which the value of the shunt capacitance ( $C$ ) can be determined for any desired supply voltage. The supply voltage must, of course, exceed the pull-in voltage of the relay.

To use the curve, determine the value of

$$\frac{E_b}{I_r R}$$

from the required supply voltage. Next, determine a value of  $f \times R$

$\times C$  and the value of the capacitor ( $C$ ) from this. Make an allowance in either  $E_b$  or  $C$  to insure reliable operation, then compute the charging resistance ( $R_b$ ) from

$$R_b = \frac{0.012}{f \times C}$$

Check the computation by determining the peak current through

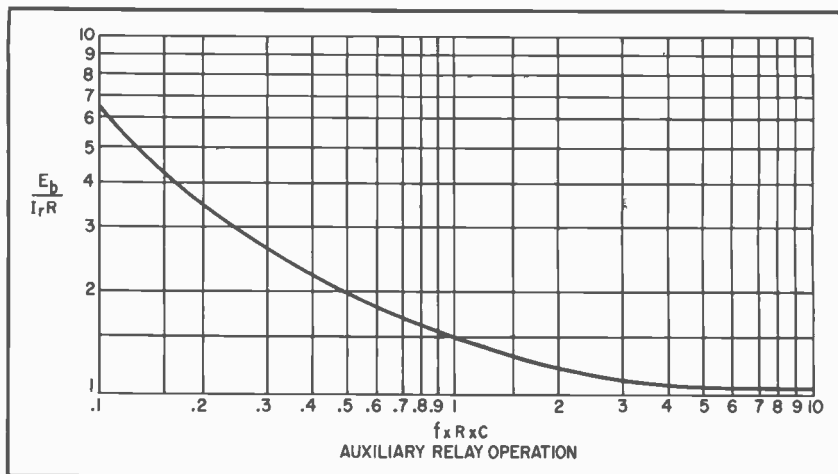


Fig. 303. Curve to determine auxiliary relay shunt capacitance.

the reed contacts and voltage across these contacts. These should not exceed 0.75 ampere and 200 volts. Note that if  $f \times R \times C$  is greater than 0.5, the value of  $E_b$  may be taken as the contact voltage. As  $f \times R \times C$  becomes smaller than 0.5, the contact voltage approaches  $2E_b$ .

Part of this basic problem is to make just one reed vibrate at a time in response to a control signal. This is due, in part, to our inability to transmit and receive absolutely pure and stable tones. Normally the wave shapes are distorted, either in the tone generator, transmitter, or receiver and they contain harmonics or secondary frequencies which cause a reed other than the desired one to vibrate.

### Considerations for proportional control

By examining the reed operation curve (Fig. 304) more closely, it is possible that some facts concerning this unit may lead to some new applications.

To achieve proportional control, we are limited to changing the amplitude of vibration and the frequency of vibration. Amplitude of

reed vibration can be controlled by governing the amount of power or by the frequency sent to the reed coil.

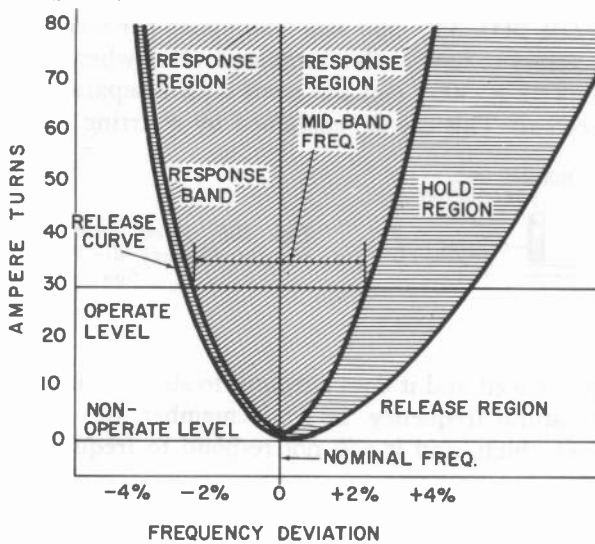


Fig. 304. Reed relay response characteristics.

Try to visualize the amplitude of a reed's vibration as varying between extremes in a gradual manner as it responds to a tone just below, exactly at and just above the reed's resonant frequency. Note

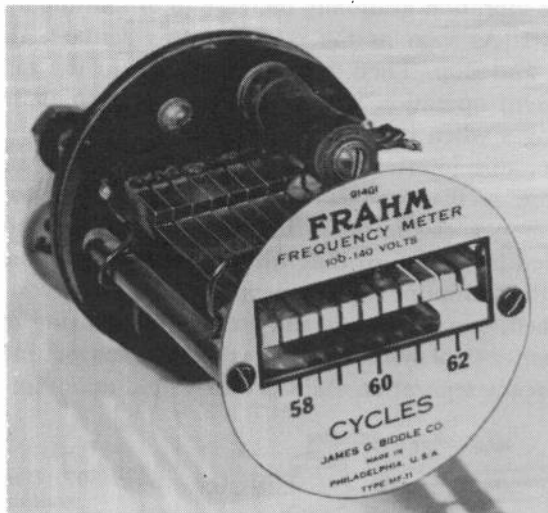


Fig. 305. Commercial frequency meter has reeds which respond to frequencies which are very close to each other. [James G. Biddle Co.]

that in many radio-control reed decoders, frequency separations of about 30 cycles are required between reeds. The frequencies generally used are 240, 270, 300, 330, 360 and 390 cycles per second.

Why is it necessary to have such a large separation when commercial frequency meters (Fig. 305) can use reeds with a separation of only 0.5 cycle per second? This can be explained by referring to Fig. 306.

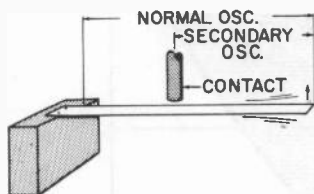


Fig. 306. Reed secondary-vibration concept. Contact also "damps" vibration.

If we energize a reed and it does not have to strike a contact, it will oscillate at its natural frequency. Its  $Q$  (remember, this is the band-pass) will be very high, and it will not respond to frequencies a few cycles away.

When the reed must strike a contact, two things happen. First, its  $Q$  is lowered, and second, at the moment of striking the contact, the effective length of the reed is changed and it vibrates with a secondary oscillation. If you were to connect a reed unit to a precision audio generator tuned exactly to the reed's natural frequency, and were to increase the gain gradually so that the reed started vibrating, you would see the vibration gradually increase in amplitude until the reed hit the contact. As soon as the reed hits this contact, the vibration will diminish and stop. Then it builds up again in the same manner. This intermittent operation results because the resonant frequency of the reed changes when it strikes the contact.

In practice, this intermittent effect is overcome by adjusting the transmitter tone oscillator so that its frequency is equal to the contact touching frequency of the reed. This is usually close enough to the reed's unloaded frequency so that vibration starts easily and continues to vibrate with maximum effectiveness.

Perhaps, then, one solution to the problem of utilizing the reed unit in proportional control systems is to have a non-contact method of using reed frequency separation abilities that would maintain a very high

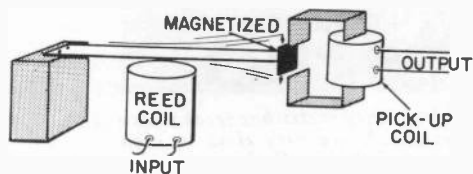


Fig. 307. Using unloaded reed as filter.

unloaded  $Q$ . One possibility is shown in Fig. 307. A small coil is positioned so that the vibrating end of the reed will affect its magnetic circuit, producing an alternating voltage proportional in strength to the amplitude of the swing of the end of the reed. This alternating voltage can then be rectified and used to control other mechanisms. There is no loading on the reed and the  $Q$  remains high. The voltage produced will be proportional to the closeness of the transmitted tone to the reed frequency.

### Reed decoded pneumatic control

Control system decoders using air pressure (see Fig 308) are a little different from those of the more familiar electrical control

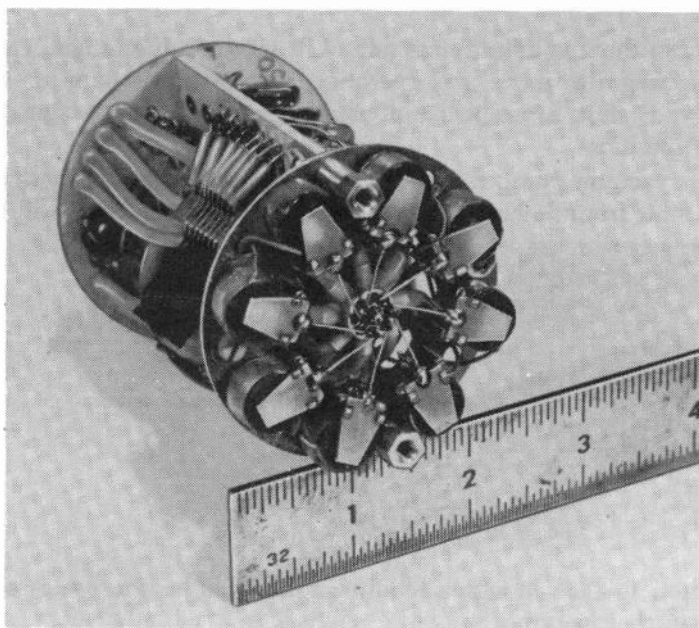


Fig. 308. *Mechanical control-system decoder uses air pressure.*

systems. Connections are by flexible rubber hose or tubing which is not so likely to break, under continuous vibration, as wires so often do.

The system (Fig. 309) works as follows: A vacuum pump, driven by the airplane motor, draws air out of a cylinder, creating a vacuum on one side of a piston, thus causing the piston to be drawn into the cylinder against the tension of a rubber band. The decoder valve manifold housed in the receiver connects to the cylinder, and the vacuum in the cylinder is applied to the manifold. From tiny valves

in the manifold, flexible tubes connect the manifold to the pneumatic servos (diaphragms) (Fig. 310) on the control mechanisms. The valves are operated by reeds and relays. When open, each valve applies the

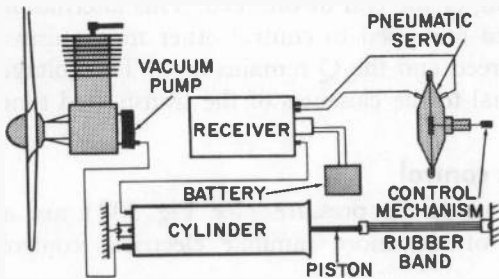


Fig. 309. *Pneumatic servo used as a control mechanism.*

vacuum in the manifold to one side of its servo or diaphragm, causing the diaphragm to move and operating its control mechanism. When the valve is shut, atmospheric pressure restores the diaphragm to its original position.

If the vacuum pump fails (let's say the motor stops), a check valve prevents air from flowing to the cylinder. The rubber band will move

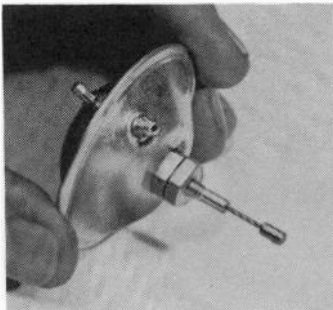


Fig. 310. *Pneumatic servo.*

the piston to pull enough vacuum in the cylinder for returning the model to the operator.

Fig. 311 illustrates another concept which might be appropriate for proportional control. In Fig. 311-a, the reed unit itself is made into a manifold for controlling air pressure or vacuum. Note that (in the small circle) the amplitude of vibration of the reed itself determines how much of the exhaust port is uncovered.

In this method, then, by transmitting a signal a little above or below the actual reed frequency, one can cause the reed to vibrate a small amount. The port would be uncovered a small amount and thus the pressure (or vacuum) to the servo would be small. The result would be a proportional deflection of the fin.

If the signal were exactly at the reed frequency, the maximum vibration would take place, giving full differential pressure and thus maximum control deflection. Fig. 311-b shows how this system is employed to control a model aircraft.

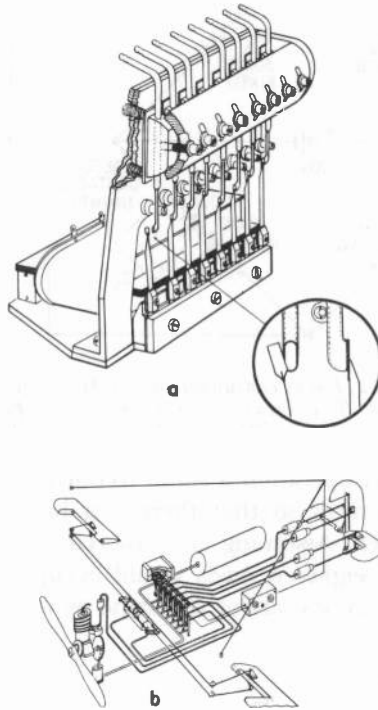


Fig. 311. *Proportional simultaneous reed-controlled pneumatic system. The reeds are only a few cycles apart.*

The vacuum system has some difficulties, especially when operating aircraft at different altitudes. The atmospheric pressure changes and thus the amount of control surface deflection can vary. If a pressure system were used, that is, if we were to let the pump create pressure, this difficulty might be overcome.

### Step-type proportional control — reed decoder

Another method for obtaining simultaneous and proportional control with a reed relay would be to use an electrical bridge which would feed a transistor-amplifier servo system. The input transistor would require very little power. Thus, the reed contact might be light enough



and of a type which would prevent loading. The idea is diagrammed in Fig. 312.

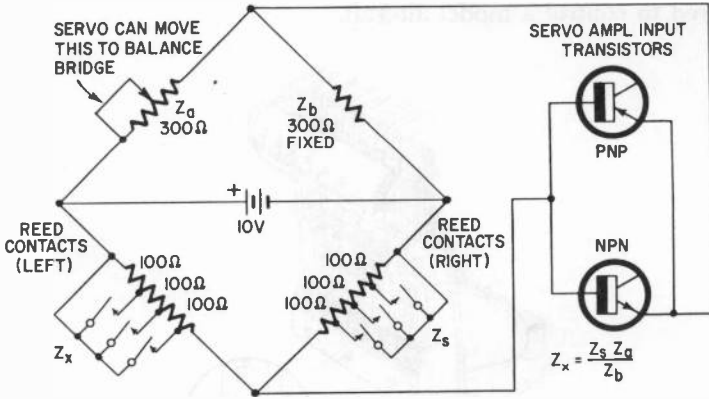


Fig. 312. Reeds can unbalance bridge to give "step" control. The reeds are 3 to 4 cycles apart. The values of the resistors can be increased, if desired.

For multichannel operation a small frequency separation should be arranged between reeds so that there can be at least six reeds per transmitter channel. Assuming a two-cycle separation, and multichannel operation, eighteen reeds would occupy a frequency span of probably 26 to 40 cycles, about the same as used for one channel at present.

### Circuit operation

When no tone is transmitted, the bridge is balanced and the servo is neutral. Moving the control stick a small amount sends out the

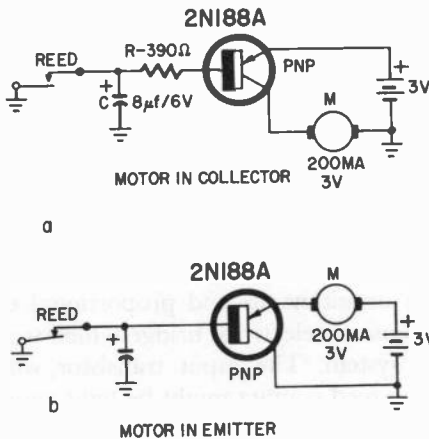


Fig. 313-a, b. Motor in the collector [a] and motor in the emitter [b].

first tone which shorts part of one bridge resistor. Because of this unbalance, a voltage is fed to the transistor servo amplifier causing the servo to operate. As the servo moves, it adjusts a potentiometer in the opposite bridge arm to reestablish the balance. The servo stops and the control surface is deflected a small amount.

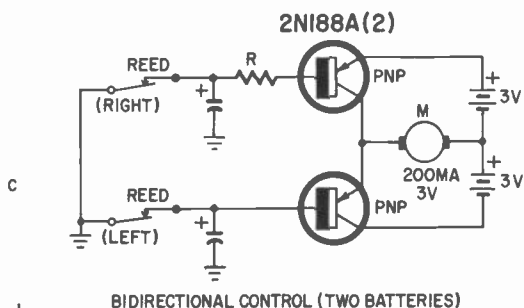
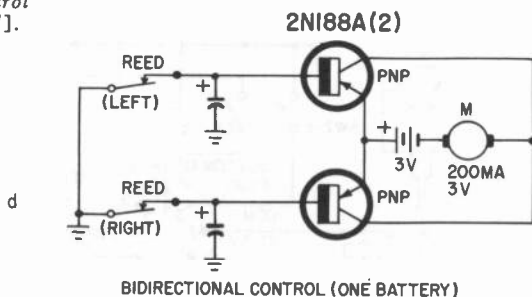


Fig. 313-c,d. Bidirectional control using two batteries [c] and bidirectional control using only one battery [d].



Moving the control stick further causes a different tone to be transmitted, shorting more of the bridge resistor. Again the servo, in moving, establishes the balance; the control surface moves a greater amount. When the tone signals to the reed relay stop (neutral joystick position, or loss of signal), the servo-controlled potentiometer, being unbalanced with respect to the other resistances, develops the necessary unbalance voltage to cause self-neutralization. This would be a fail-safe feature.

This is a proven system. It is fail-safe and would give some proportional and simultaneous control, although the proportional aspect would be in steps instead of a completely smooth variable transition. Fig. 313 gives some of the possible methods of connecting a relay reed, through a transistor, to a servo motor. There will be more on the servo system later.

Transistors are used to replace relays as well as tubes. Fig. 314 shows the circuit for one system. With proper feedback provided, this

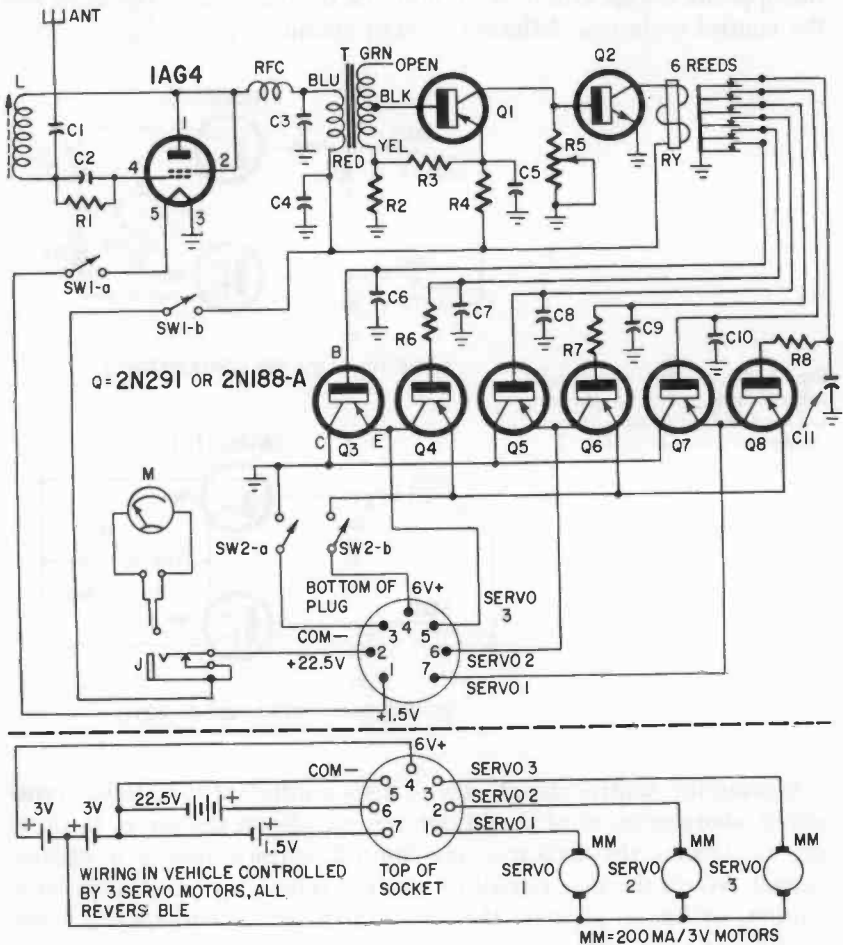


Fig. 314. Complete reed-and-transistor-controlled servo radio-control unit.

circuit would form the basis for a discrete-step simultaneous proportional system.

### Commutating tones and reed decoder for simultaneous control

Another concept in the quest for simultaneous control systems is that of commutating tones. Consider six tone generators feeding the

contacts of a commutating switch. As the arm rotates it passes on each tone, in turn, to the transmitter modulator. If the commutation speed is high, an almost simultaneous transmission takes place and the full modulation (100%) is effective on each tone.

Remember that it takes an instant for a reed to build up to maximum vibration amplitude, and an instant for it to die down once excited. We take advantage of this latter fact. We depress one, two or all control switches. The commutator takes care of sending out the tones, whatever their number. The individual reeds vibrate and keep vibrating due to their own kinetic energy, even though the excitations are but impulses. The impulses are, of course, repeated frequently

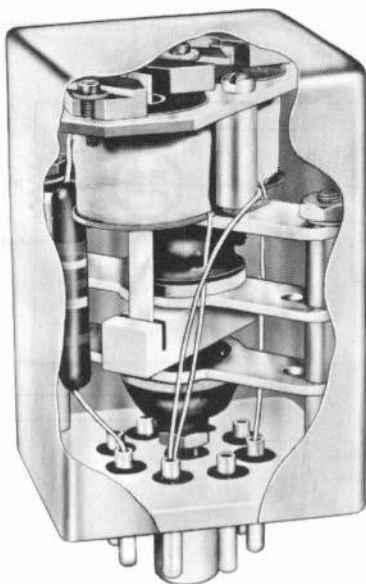


Fig. 315. Resonant-reed [tuning-fork] generator control for use in tone generator circuit. [James G. Biddle Co.]

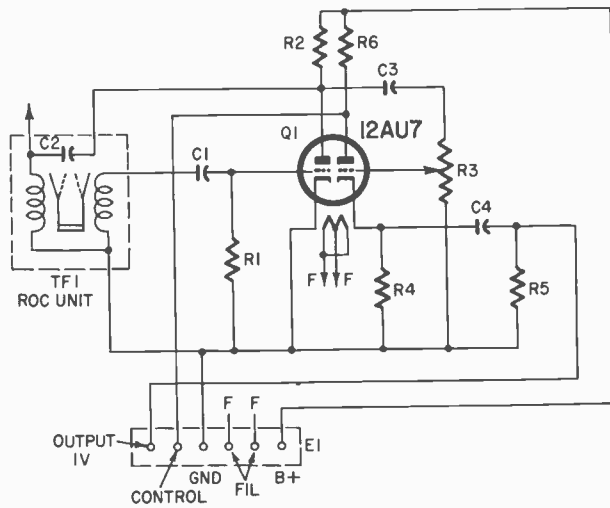
because of the rapidity of commutation. Effectively, full tone energy is present in the reed coil at any instant.

It is interesting to note that through the ability to select any combination of six (or more) tones, and therefore any combination of six relays operated by the six reeds, up to 64 individual control functions can be accomplished.

## The tone generation problem

We cannot leave the concept of reed units as frequency decoders without mentioning the tone-generation problem. We have indicated the many possibilities for use of this decoder provided we can obtain narrower separations of the reeds. We must remember that with closer reed frequencies we will require more precise control over the generated tones. These must be purer than those currently used.

Tone wheels might be used where the speed of the wheel directly governs the frequency and thus allows precision control by regulating motor speed. Pulse generating circuits make a precise number of cycles per second which can be filtered and smoothed into pure sine waves. Whether tuned circuits, tuning forks or any other mechanical



**Capacitors:** C1— $.1 \mu\text{f}$ , 400 v; C2—part of TF1; C3— $.05 \mu\text{f}$ , 400 v; C4— $2 \mu\text{f}$  metallized (paper), 200 v (all  $\pm 20\%$ )

**Resistors:** R1—1 megohm,  $\pm 10\%$ ,  $\frac{1}{2}$  watt; R2—270K,  $\pm 10\%$ , 1 watt; R3—250K, locking type potentiometer; R4—750 ohms,  $\pm 5\%$ , 2 watts; R5—270K,  $\pm 10\%$ ,  $\frac{1}{2}$  watt

**Tube:** Q1—12AU7, 5814-A, 5814-WA or 6189

**Tone source:** TF1—Frahm oscillator control, ROC unit (frequency as required)

**Miscellaneous:** E1—terminal strip (Cinch-Jones 6-141-Y or equivalent); tube socket, 9-pin (shield type) mica-filled (Elco ST 169 or equivalent); tube shield, 9-pin, 1-15/16 inches high, ventilated (Elco 190V or equivalent); phenolic panel, 3 x 6-3/4 x 3/16 inches; hardware

Fig. 316. Tone generator using tuning-fork reed control.

method is used, remember that the tones must be pure, exact, variable, and should not be harmonically related. Since each reed has a definite bandwidth the tones should not overlap bandwidths. Fig. 315 shows a cutaway of one plug-in tone-generator stabilization device, and Fig.

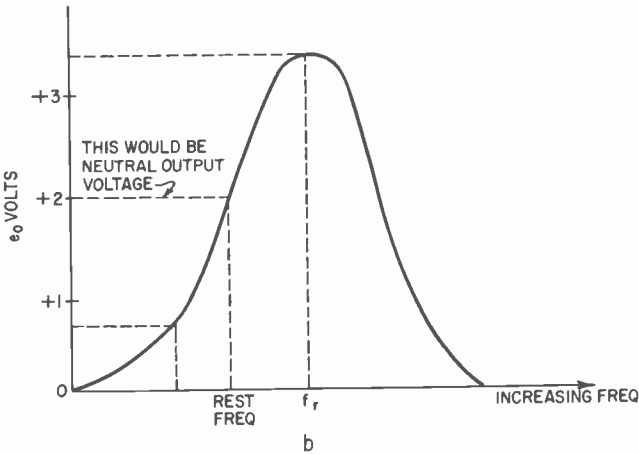
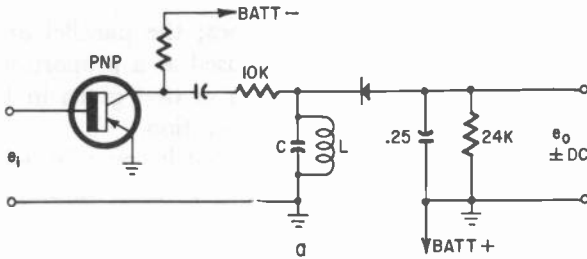


Fig. 317. Slope detector gives only positive or negative voltage output — not both.

316 shows a circuit for this unit to produce the tones desired. Circuits for transistors are also used.

### Discriminators and filters

Since one goal is to be able to control all functions simultaneously and because the reed type frequency decoder is limited in this respect, let's examine some other methods of obtaining proportional control.

Perhaps, next to the reed decoder, the filter-discriminator decoder is most important. Here we transmit several tones at one time, using a filter which separates the tones. Each tone is then converted into a dc control voltage through a slope detector or a discriminator. In some

applications the filters may be a separate section of the circuit; in others the frequency selectivity characteristic of the discriminator itself will serve to produce the filter effect.

At the present time, the filter most commonly used to effect tone separation is the simple series or parallel L-C type. Series types are more commonly used with vacuum tubes; the parallel arrangement with transistors. This L-C filter can be used as a proportional control decoder by operating it in a circuit such as that given in Fig. 317-a. The curve of Fig. 317-b illustrates the operation.

If the transmitted tone is adjusted so that it coincides with the rest frequency, the voltage output  $e_o$  will be more than minimum and less than the maximum obtainable. The output on the graph indicates

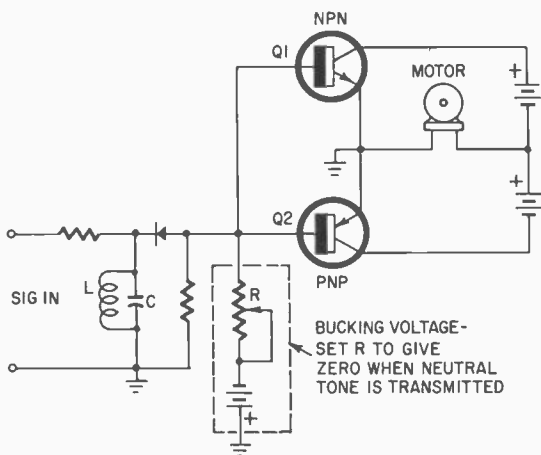


Fig. 318. *Modification of slope discriminator.*

plus 2 volts. If the tone frequency is increased, up to  $f_r$  (the resonant frequency of the tuned circuit), the voltage output increases to about  $3\frac{1}{2}$  volts. Lowering the frequency below the rest value will reduce the voltage output to about 1 volt assuming that we want to operate on the more linear part of the curve. The voltage output,  $e_o$ , varies with frequency and thus becomes suitable for proportional control but note that it does not change polarity. The next problem then is how to get plus, zero and minus voltages using this type circuit.

Furnishing, within the decoder, a circuit which will provide a reference voltage (which would oppose the output of the slope detector) will produce the desired plus, zero and minus voltage outputs. Refer

to Fig. 318. Here, the value of resistor  $R$  is adjusted so that the voltage at the bases of the two transistors is zero when the rest frequency voltage is produced by the detector. When the output voltage increases, due to an increase in tone frequency, this plus voltage is greater than the reference negative voltage and thus a plus voltage is applied to the bases of  $Q1$  and  $Q2$ . The n-p-n transistor will conduct and drive a servo motor in one direction.

When the signal frequency is decreased, the reference voltage is now the greater and thus the sum of the two will be negative. Now transistor  $Q2$  conducts a current in the opposite direction through the

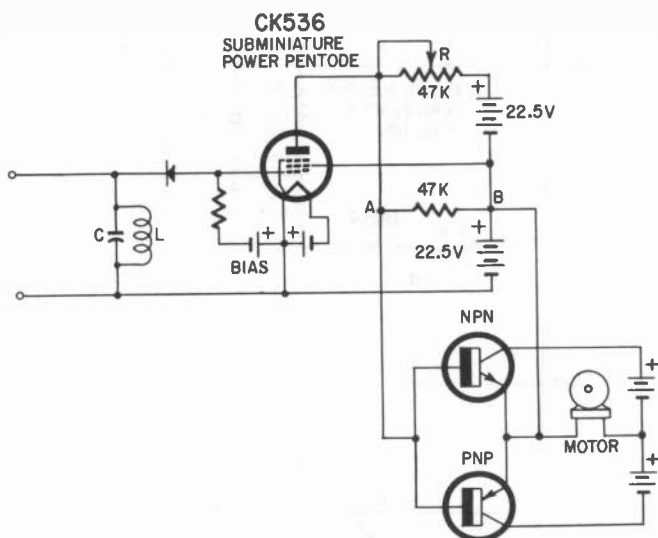


Fig. 319. Using a tube with a tuned circuit gives discriminator action. Adjust  $R$  for zero voltage between  $A$  and  $B$  when "rest" frequency is transmitted.

motor in its output. This is the desired condition. We have a complete discriminator action using one tuned circuit in a simple arrangement.

A word of caution about using an opposition voltage such as this. Unless this voltage can be obtained from the signal itself, the loss of a signal would result in only this opposition voltage being present. This would mean a full deflection of a control surface and possible disaster. This type of control would be most suitable in a controlling device where signal loss would not mean a crash.

Fig. 319 shows how this same idea can be applied to a vacuum tube. In this circuit the tube bias will have to be adjusted to set the



tube current at half its maximum class-A value. A variable resistor in the grid circuit will not work since the grid draws no current.

An opposition voltage derived from the signal itself is used in the circuit in Fig. 320-a. Here one diode (D1) rectifies the signal directly and it is balanced against the signal produced from the diode (D2) connected to the tuned circuit. One half of the circuit thus is frequency selective, the other is not.

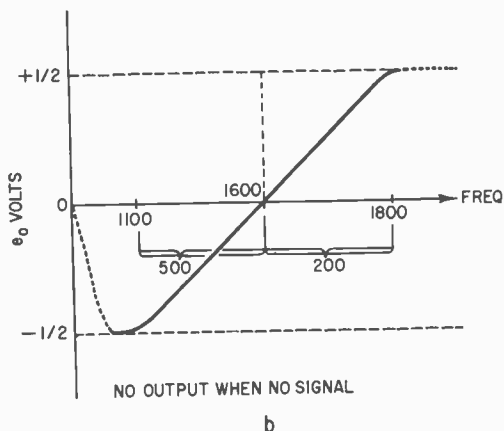
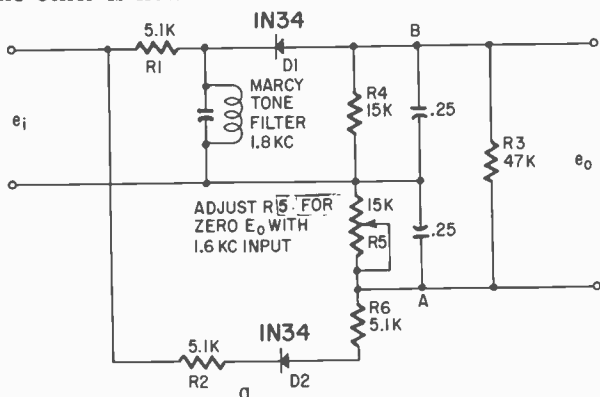


Fig. 320. Discriminator using bucking voltage derived from signal. Adjust  $R_5$  for zero output voltage [ $e_o$ ] with 1600-cycle input. The curve shows that there is no output when there is no signal.

In this circuit,  $R_1$  and  $R_2$  are simply isolation resistors and have the values shown. The diodes must be connected so that the cathodes are in the same direction.  $R_5$  and  $R_6$  allow proportioning of the non-frequency-selective voltage to the correct value to balance against

that produced across R4. The two capacitors and the common load resistor (R3) allow the balancing action to take place.

A tone from an audio generator is fed into the input as  $e_i$ . A high resistance voltmeter (20,000 ohms/volt or a vacuum-tube type) set to about a 10-volt scale can now be connected across R4. The audio generator is adjusted to give a maximum reading. Next the audio generator is tuned carefully away from this frequency to a new frequency where the voltage across R4 is just zero. Now the meter is connected across R5 and its value is adjusted to give a reading at least  $\frac{3}{4}$  the value obtained across R4 when the generator is tuned to resonance with the tuned circuit. Finally, the meter is connected across the load, points A and B. The generator is retuned toward the frequency which gave a maximum across the tuned circuit. At some value the voltage will be zero. Now the generator dial is moved first higher and then lower in frequency and R5 is adjusted until a good linear plus and minus swing is obtained. An indication of the results obtained in one test using a filter tuned to 1,600 cps is shown in the graph of Fig. 320-b.

The difficulty with this kind of circuit is that since only one branch is frequency selective, it normally would be suitable for only one proportional control function. One could not obtain multichannel proportional control without adding another frequency selective element in the R1 - R4 side of the circuit or preceding this circuit with a band-pass filter. This circuit however, is fail safe. In the event of signal loss there is no output and therefore the servo will return to a neutral position.

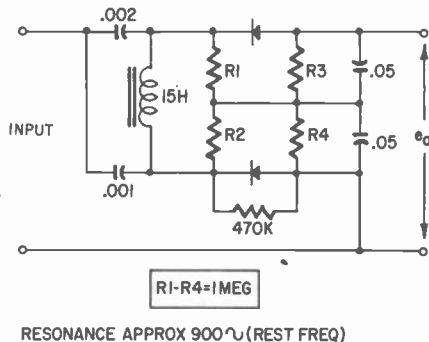


Fig 321. Slope detector using split capacitor output.

Another type of slope detector is shown in Fig. 321. This detector, although connected somewhat differently, produces about the same effect as those previously described.

## R-C type discriminators

In an effort to obtain a discriminator which could be as small as possible, the concept of using an R-C (resistance-capacitance) network to produce the positive and negative output voltages needed for proportional control was investigated. The theory was simply that at the rest frequency the capacitive reactance of a capacitor could be made equal to that of a resistor in a bridge circuit. As the frequency would decrease, the reactance would increase, unbalancing the bridge in one direction, and as the frequency increased the capacitive reactance would decrease, unbalancing the bridge in the opposite direction. A

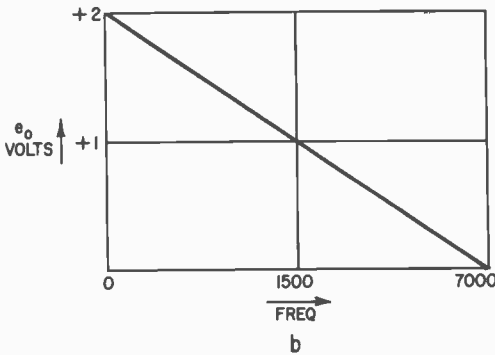
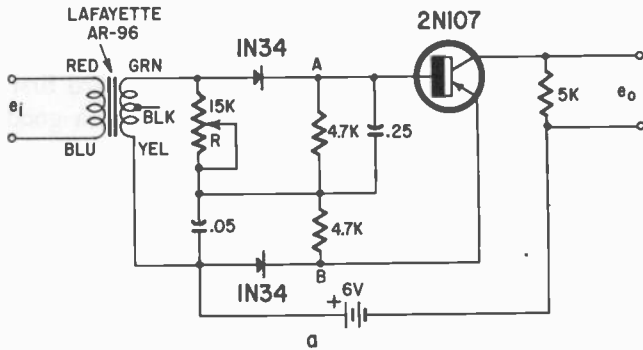


Fig. 322. R-C discriminator. Set  $R$  to zero with input signal at "rest" frequency. At 3,000 cycles, the voltage across A-B is zero. It increases to +1 volt at 9,000 cycles and becomes -1 volt at 1,000. Signal loss gives zero output.

transformer was used to feed the network to provide isolation from the source. The circuit is shown in Fig. 322-a. Fig. 322-b shows the test results with the values specified.

The output of this circuit was so low that a transistor had to be used as a driver for the servo amplifier. Note also that  $R$  is variable. This could be a feedback potentiometer which is driven by the servo motor to reestablish bridge balance.

In general, the response was quite broad, as shown in Fig. 322-b and indicated that if more voltage amplifying stages were used, the operating band of frequencies could be reduced, as is necessary for multichannel control.

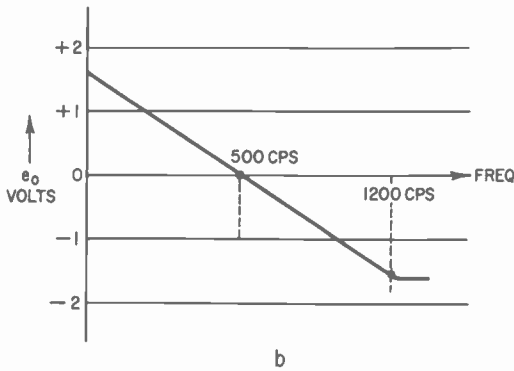
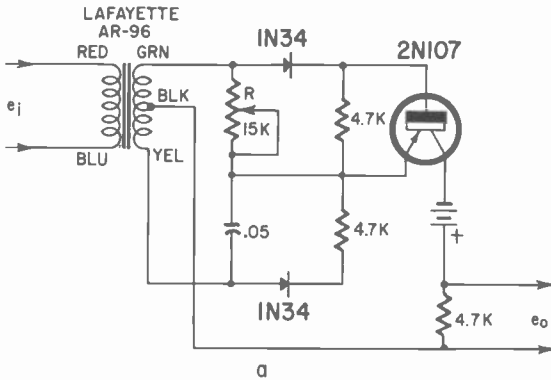


Fig. 323. Amplitude and frequency discriminator. Set  $R$  for zero output voltage [ $e_o$ ] at 500 cycles.

The circuit in Fig. 323-a is also an amplitude detector producing a plus or minus output by varying the amplitude of the input signal. It still retains the ability to produce control signals with frequency variations as shown in the graph of Fig. 323-b, when the amplitude is adjusted to a given value.

## Balanced (Foster-Seeley) type discriminators

A Foster-Seeley type discriminator was used at audio frequencies. The circuit is shown in Fig. 324. Although a relatively low  $Q$  trans-

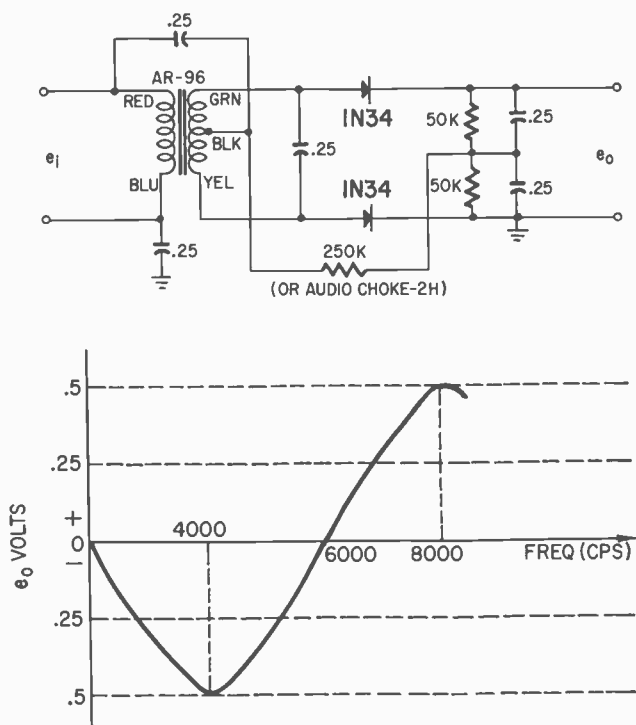
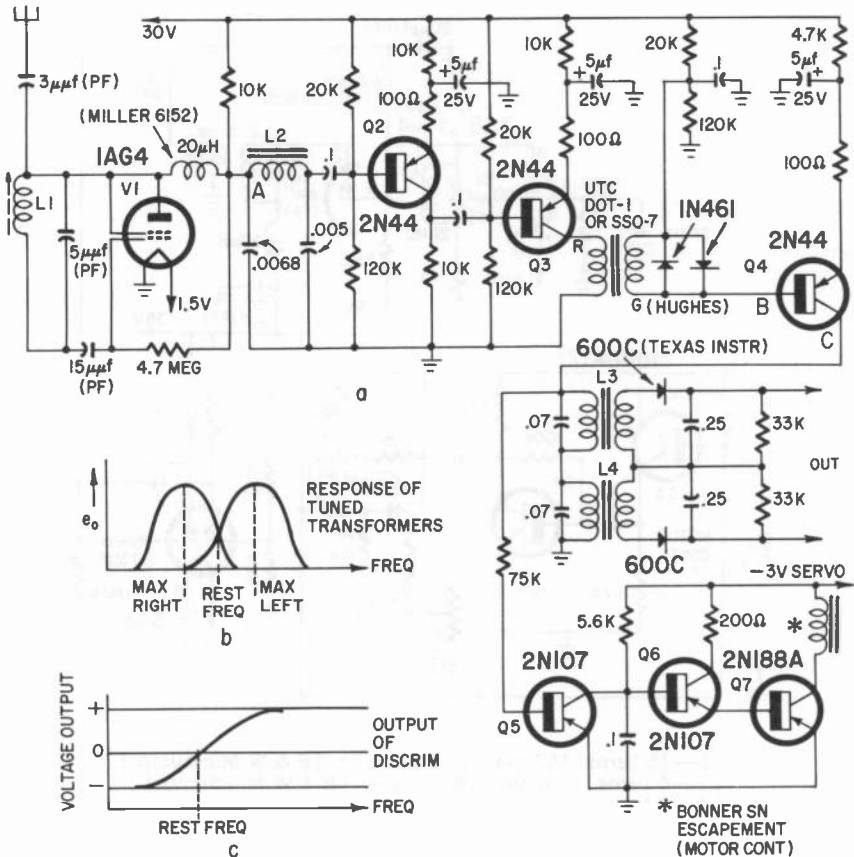


Fig. 324. Foster-Seeley type discriminator. Signal loss gives zero output. Large input signal is required. Performance may be improved with high  $Q$  transformer.

former is used, discriminator action was obtained but with relatively low output voltage. There is no output unless a high driving signal is used. However, by using a high  $Q$  transformer and varying the circuit values, it may result in a discriminator adequate for radio-control purposes.

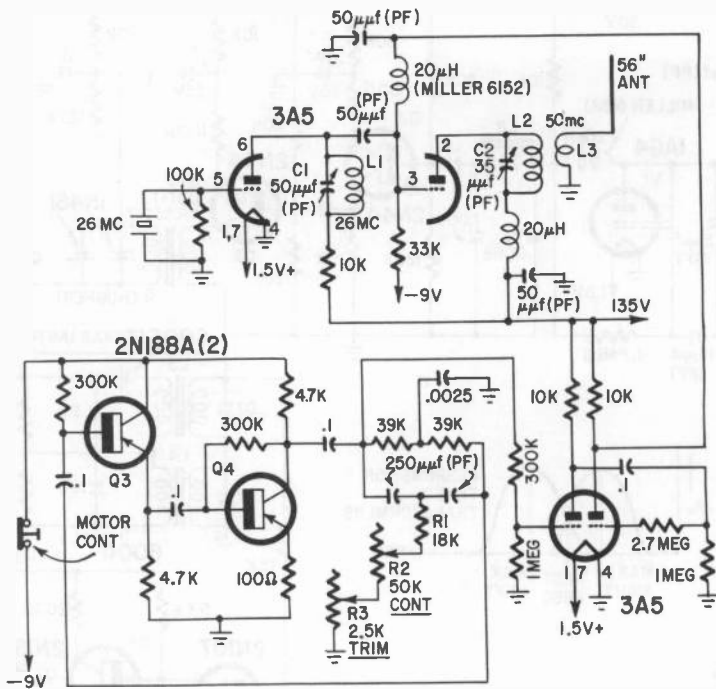
Two tuned transformers have been used to obtain a discriminator suitable for simultaneous proportional radio control. This circuit is shown in Fig. 325-a. Note that this is a complete one-channel system. Fig. 325-b shows how, through stagger tuning of the two transformers, one is able to produce different voltage maximums at different frequencies. When the rectified output of L3 is negative to that of L4 the discriminator curve of Fig. 325-c is obtained.



L1—15 turns No. 28 enameled wire on CTC PLS 6-2C4 LD coil form  
 L2—1,200 turns No. 38 enameled wire on Arnold Engineering Co. A050056-2 toroid form  
 L3, L4—primary, 300 turns No. 32 enameled wire on A050056-2 toroid form  
 L3, L4—secondary, 350 turns No. 38 enameled wire wound over primary  
 Resistors—all  $\frac{1}{2}$  watt  
 Capacitors—3, 5 and 15  $\mu\text{f}$  are silver mica

Fig. 325. Receiver for complete proportional-control R-C system. This is a single-channel receiver for 50 mc.

To obtain a discriminator which would produce the plus, zero and minus output voltages for the narrowest range of frequencies using commercial filters, the circuit of Fig. 326-a was constructed. Two identical 1,800 cycle filters were modified to retune them to 1,550 and 2,000 cycles. To decrease the frequency an additional capacitor of .1  $\mu\text{f}$  was added across one unit.



- L1—15 turns,  $\frac{1}{2}$ " diam., 10 turns/in. [B & W Miniductor]  
 L2—4 turns, 1" diam., 10 turns/in. [B & W Miniductor]  
 L3—2-turn loop  
 Resistors—all  $\frac{1}{2}$  watt  
 Capacitors—C1,  $50 \mu\text{mf}$ , Hammarlund MAPC-50  
 C2,  $35 \mu\text{mf}$ , Hammarlund MAPC-35

Fig. 325 [continued]. 50 mc proportional-control transmitter.

The second unit was carefully opened so that all of the bright wire wrapping could be removed. We reduced the number of turns down to the black wire which is the standard winding for these filters. The only requirement was to increase the resonant frequency of this second filter about 500 cycles above the first. One might slide out the core to do this if the proper glue-softening agent is used.

This circuit gives excellent discriminator action (Fig. 326-b) and is nonresponsive to frequencies below 1,000 cycles and above 2,500 cycles. This means that similar discriminators could be used if their resting frequencies were about 500, 4,000 and 8,000 or 9,000 cycles. Three such discriminators could operate with sufficient separation between them so that no crosstalk or "spillover" would occur.

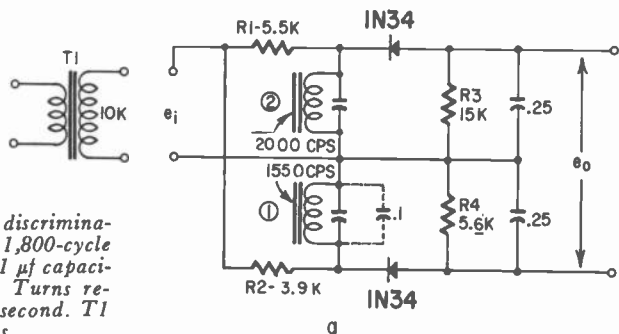
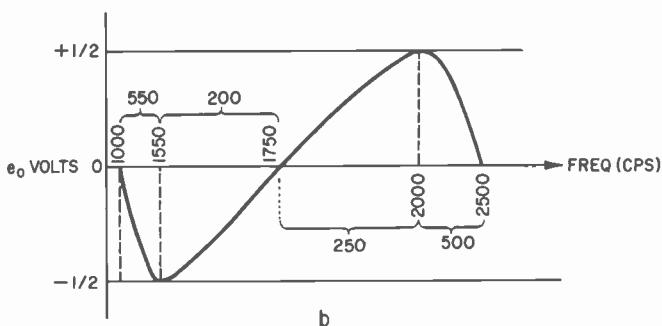


Fig. 326. Two-filter discriminator. Two identical 1,800-cycle tone filters used. A 0.1  $\mu$ f capacitor is added to one. Turns removed from coil of second. T1 used in tests.



The values of R2 and R3 are adjusted to balance the output to zero and give good linearity. One might use variable resistances here, adjust them for proper response, then replace with fixed values. The resistance values used at R3 and R4 were just arbitrary selections as to range. One might use much higher values as long as R3 is made adjustable to obtain the balance and linearity required.

Two other detector circuits which can be adapted to the proportional control problem are given in Figs. 327 and 328. Although both employ transformers, there is difficulty in getting transformers small

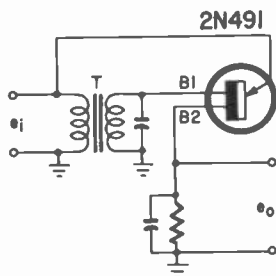


Fig. 327. Symmetrical transistor discriminator. Transformer T must be a high-Q unit.



enough to make their use feasible. High Q transformers will produce the best results, and in both cases the transformers must be capable of

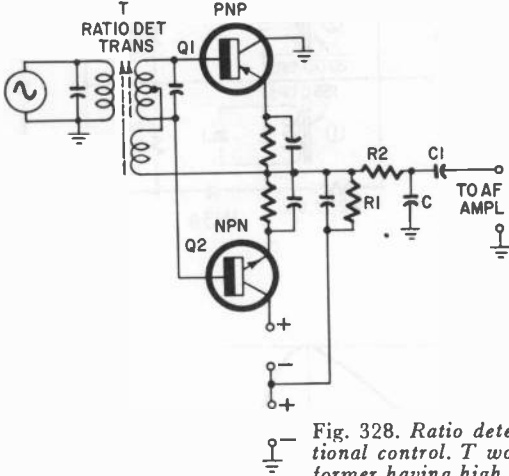


Fig. 328. Ratio detector might be used for proportional control. T would have to be an audio transformer having high Q and a third winding. R2 and C, de-emphasis network for FM receiver use, can be omitted. Output signal is developed across R1.

being tuned to the desired frequency, as was done in the circuit in Fig. 326.

It is possible to use pulse rates instead of tones, particularly with

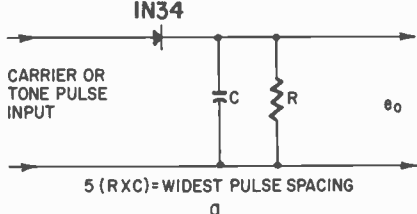
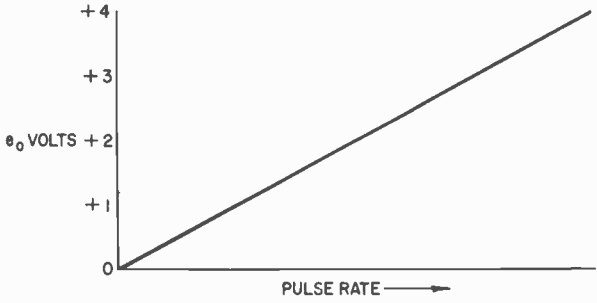


Fig. 329. Detector circuit [a] converts varying pulse rate to a varying dc voltage proportional to the rate [b].



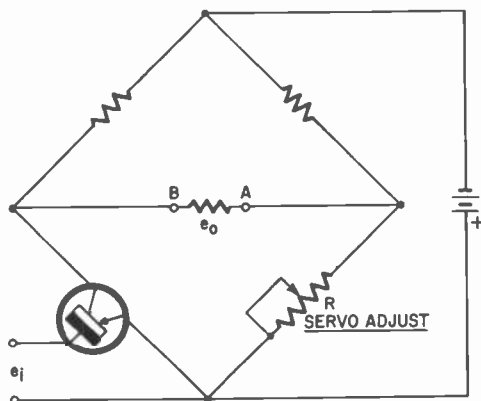
e<sub>o</sub> VOLTAGE INCREASES AS PULSE RATE INCREASES BUT ALWAYS SAME POLARITY

b

single-channel equipment. The detector circuit of Fig. 329-a will convert a varying pulse rate into a dc voltage that is proportional to the rate (Fig. 329-b).

Although it gives only a unidirectional voltage change, this can be used to operate another circuit which, in turn, will convert it to the necessary plus and minus voltages to drive the servo amplifier. Fig. 330 illustrates one such circuit. This is basically a bridge circuit with a transistor connected in one leg. A variation in the impedance of the

Fig. 330. An increase or decrease of  $e_i$  can give a plus or minus polarity of  $e_o$  at A with respect to B.



transistor (either higher or lower than  $R$ ) will cause a polarity change between points A and B. These points in turn are connected to the bases of a complementary-symmetry transistor servo amplifier.

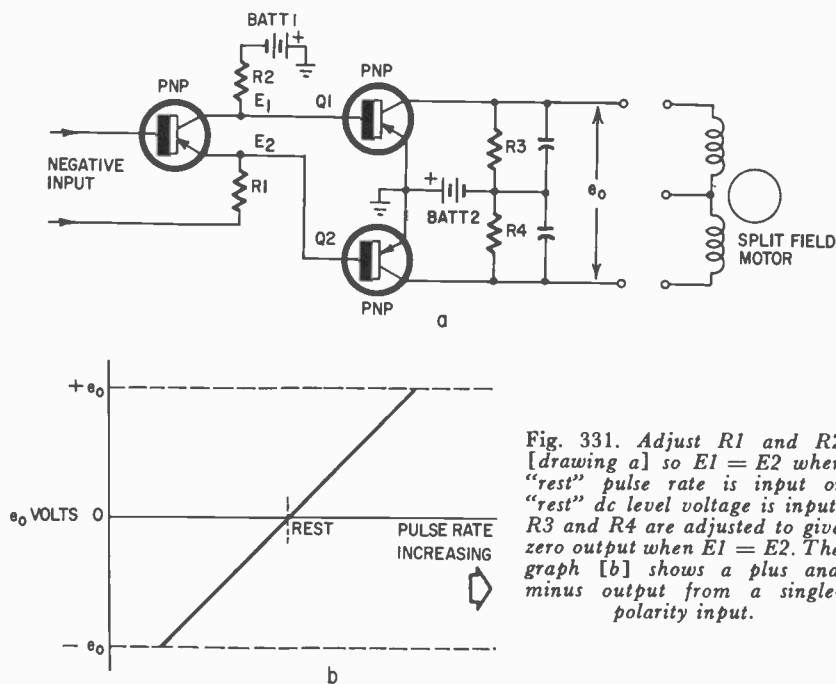
The servo motor can be made to vary resistance  $R$  in such a direction as to rebalance the bridge whenever the transistor voltage input  $e_i$  causes an unbalance in its leg. Proportional control is thus achieved.

Another method of using the output of a detector such as that in Fig. 329-a would be to feed the amplifier circuit in Fig. 331-a. In this case, the input transistor would have a negative input by having the correct polarity from the diode circuit of Fig. 329. With the rest pulse rate being transmitted, the voltages  $E_1$  and  $E_2$  from the input transistor are adjusted for equal voltage drop values by varying  $R_1$  and  $R_2$ .

Since ground is positive (battery B1 having its plus terminal connected to ground), the voltages at the collector and emitter of the first transistor would be negative with respect to ground. This would cause  $Q_1$  and  $Q_2$  to conduct. Assuming that both transistors are identical (and if they are not, then  $R_1$  and  $R_2$  could be adjusted so that they do conduct an equal amount) the voltage drops across  $R_3$  and  $R_4$  would be equal and  $e_o$  would be zero. The graph in Fig. 331-b

shows how  $e_0$  might vary as the pulse rate was changed to a higher or lower value than the resting rate. This voltage then could be used to drive a servo amplifier as previously mentioned. The use of a split field winding motor instead of R3 and R4 is another possibility. The circuit could drive a motor directly provided its current is low enough.

A disadvantage of this circuit is that, in the event of the loss of the



control signal, the circuit would unbalance and cause a full deflection of the control surface. To prevent this a fail-safe relay might be incorporated. This relay is so wired into the circuit that if the pulse rate or input voltage drops below a certain value, the relay contacts (Fig. 332) would break the circuit to the servo amplifier input. The servo amplifier would then neutralize; this degree of neutralization would have been previously set by the adjustment of  $R$ .

There are many ways in which the relay contacts can be made to remain open or closed as long as there is a pulse rate existing in a circuit. The basic idea is to feed the input signal to a second transistor amplifier which, for example, would conduct as long as the pulses were present and stop conducting when the pulses stopped or the rate

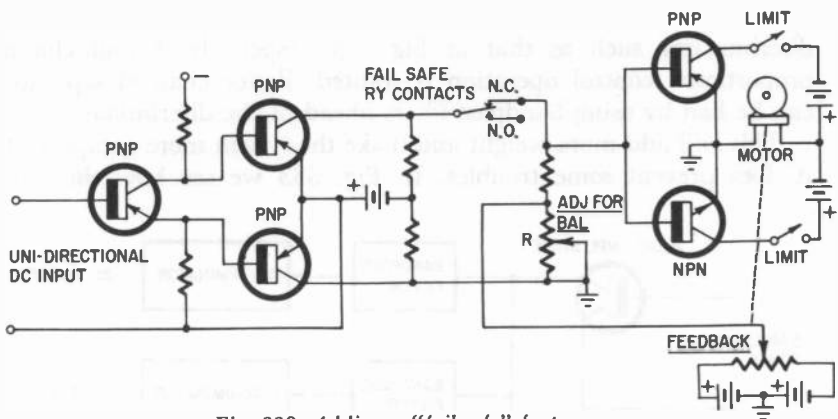


Fig. 332. Adding a "fail-safe" feature.

became too slow to hold the relay contacts closed. In this case, the relay shown in Fig. 332 would have circuit continuity through its armature and normally open contact instead of as shown.

### Narrowing the bandpass

There are many circuits which convert a change in the audio tone or pulse rate into a plus or minus control voltage, depending upon whether the tone, or pulse rate, increases or decreases from the resting frequency. The next problem, then, is to consider how to achieve better channel separation especially when using the R-C type separator in which only one component of the circuit is frequency sensitive.

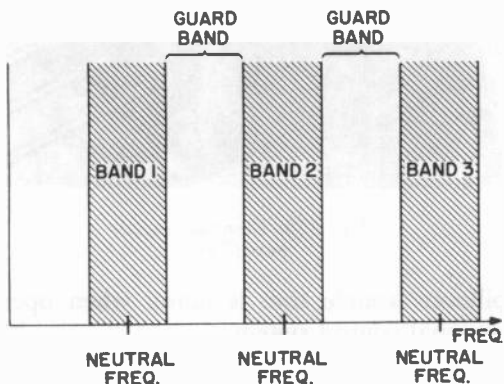


Fig. 333. Separation of audio spectrum into bands for proportional control.

Better channel separation is useful even when using a relatively narrow discriminator such as that in Fig. 326, especially if multichannel proportional control operation is wanted. Better channel separation can be had by using bandpass filters ahead of the discriminators.

This will add more weight and make the system more complex, but it does prevent some troubles. In Fig. 333 we see how the audio

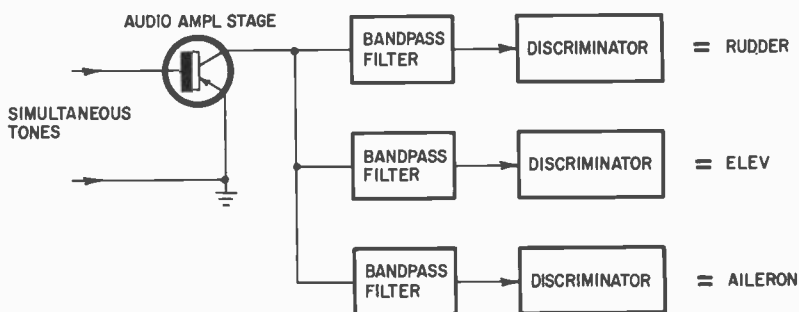


Fig. 334. Bandpass filters are used in front of discriminator.

spectrum may be split into band 1, band 2 and band 3 by means of filters. The signal from the filters is fed to the discriminators (Fig. 334)

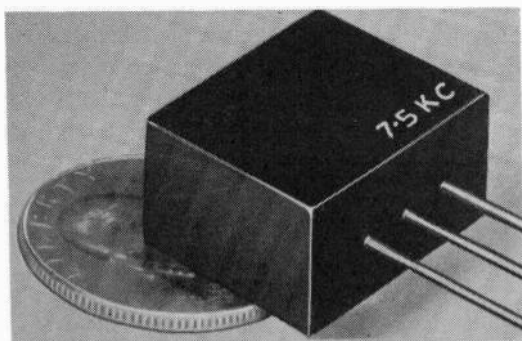


Fig. 335. Compact band-pass filter.

to prevent spillover trouble that is found when operating a multi-channel proportional control system.

A bandpass filter is shown in Fig. 335. Note its size as compared to the 25-cent piece. The frequency of this particular one is 7.5 kc. By using special coils, lower frequency filters but slightly larger in size are

available. Fig. 336 shows an electromechanical type of bandpass filter which can also be used.

**Circuits and components**

Having established a need for such devices, let us now turn our attention to some of the circuitry, components and calculations involved when using bandpass filters.

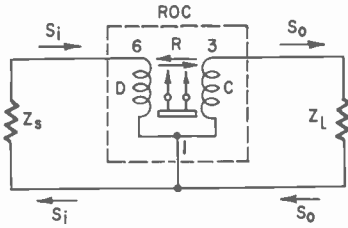
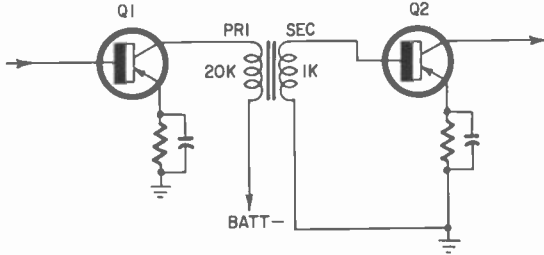
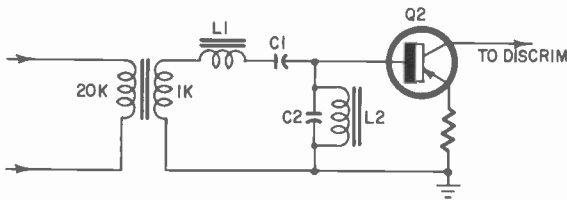


Fig. 336. Electromechanical bandpass filter. [ $Z_s$ , signal source impedance;  $Z_L$ , signal load impedance;  $S_i$ , input signal of resonant frequency;  $S_o$ , output signal of resonant frequency; ROC, electromechanical bandpass filter; D, signal input coil; C, signal output coil; R, resonant reeds.]

Fig. 337-a shows a basic transformer coupling circuit between two amplifiers. Note that it is necessary to match impedances. The transformer takes care of this impedance matching problem between the



NORMAL COUPLING, SECONDARY MATCHES TRANSISTOR INPUT  
a



"L" SINGLE ARM CONFIGURATION  
b

Fig. 337. Interstage transformer provides correct input impedance; transistor correct termination impedance. Typical transformer coupling [a] and single arm "L" configuration [b].

collector of the first transistor and the base of the second transistor by providing a 20,000-ohm impedance winding for the collector circuit and a 1,000-ohm impedance winding for the base-emitter circuit.

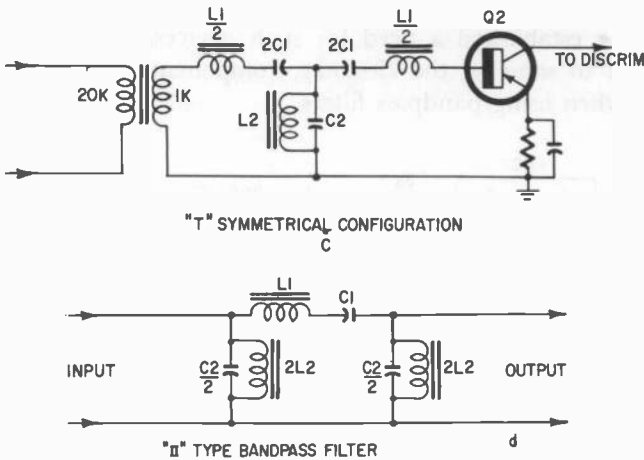


Fig. 337 [continued]. "T" symmetrical configuration [c] and  $\pi$ -type bandpass filter [d].

Fig. 337-b shows a basic bandpass filter which is placed between the transformer secondary and the second transistor. In placing it here, the input to the filter is 1,000 ohms and the terminating resistance (the emitter-base impedance) of transistor  $Q2$  is 1,000 ohms. Note also that this bandpass filter consists of a series resonant circuit  $L1$ ,  $C1$  and a parallel resonant circuit  $L2$ ,  $C2$ . If the series circuit is tuned correctly, it will let the frequencies we desire pass easily and reject those we don't want. The parallel circuit, on the other hand, will present a shunting circuit to the frequencies we don't want and will present a high impedance to those we do want to send on to the transistor  $Q2$ .

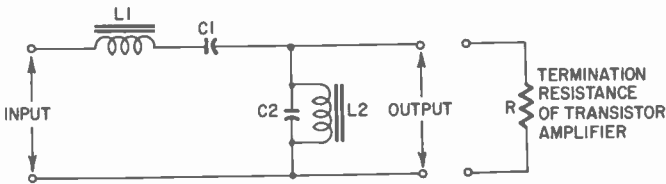
Filters generally fall into two categories, or perhaps we should say three categories; the L type shown in Fig. 337-b, the T type in Fig. 337-c, and the so called  $\pi$  (Pi) type in Fig. 337-d. Basically, we design an L section and obtain values for the chokes and capacitors; then we can rearrange the circuit according to Figs. 337-c or d by simply making the values either half or twice those calculated for the L section alone.

The T and  $\pi$  type filters are symmetrical; that is, regardless from which end of the circuit you start at, there are the same value components. This means, in turn, that when we design a symmetrical filter

to work into a given impedance, that same impedance will be reflected back through to the input. For example, if the characteristic impedance of a T or  $\pi$  type filter is 500 ohms, its terminating resistance should be 500 ohms and its input should be 500 ohms. We can cascade additional filter sections to obtain a sharper bandpass. In Fig. 337-c the filter is placed between the 1,000-ohm transformer winding and the transistor base so that input and output impedance of the filter are both 1,000 ohms.

### Filter calculations

To determine what values of capacitors and inductors to use to give a certain bandpass (and to match impedances at the same time), use the method of calculation given in Fig. 338.



$$L1 = \frac{R}{(3.14)(f_2 - f_1)} \quad L2 = \frac{(f_2 - f_1) R}{(12.56)(f_1 f_2)}$$

$$C1 = \frac{(f_2 - f_1)(10^6)}{(12.56)(f_2)(f_1)(R)} \quad C2 = \frac{10^6}{3.14(f_2 - f_1)(R)}$$

(L in henries; C in microfarads)

Problem: Pass 1,000 to 2,500 cps      1000-ohm termination

$$\left. \begin{aligned} L1 &= \frac{1000}{(3.14)(2500 - 1000)} = .21 \text{ henry} \\ C1 &= \frac{2500 - 1000 \times 10^6}{(12.56)(2500)(1000)(1000)} = .0478 \mu\text{f} \end{aligned} \right\} \begin{aligned} F_R &= \frac{1}{6.28 \sqrt{LC}} \\ &= 1592 \text{ cps} \end{aligned}$$

$$\left. \begin{aligned} L2 &= \frac{(2500 - 1000)(1000)}{(12.56)(2500)(1000)} = .0478 \text{ henry} \\ C2 &= \frac{10^6}{(3.14)(2500 - 1000)(1000)} = .212 \mu\text{f} \end{aligned} \right\} \begin{aligned} F_R &= \frac{1}{6.28 \sqrt{LC}} \\ &= 1592 \text{ cps} \end{aligned}$$

Fig. 338. Bandpass filter calculations.



The lower bandpass limit is  $f_1$  and  $f_2$  is the upper bandpass limit. As an example we will use the frequencies of 1,000 cycles and 2,500 cycles, which will work with the discriminator in Fig. 327. This filter incorporated into the circuit ahead of the discriminator will prevent cross coupling when used in a simultaneous operation multitone radio control system. The calculations are straightforward as shown, and can be used for any other band of frequencies that might be desired. Note that we have shown the resonant frequency formula. This was used as a quick check to be sure we did not make a mistake in values.

To solve this equation, insert the values calculated for the L's and

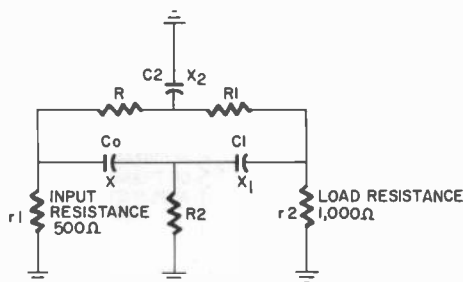


Fig. 339. Twin-T filter showing resistance of source feeding  $T$  as 500 ohms and load the  $T$  feeds as 1,000 ohms.

C's and obtain a resonant frequency in the bandpass. In this case both were resonant around 1,600 cycles per second.

### R-C filters

We should not leave the subject of filters without mentioning the most selective of the RC filters — the parallel or Twin-T (Fig. 339) — as another possible solution to the problem of filters.

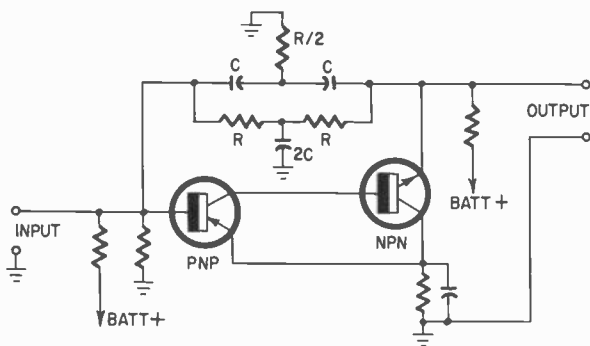


Fig. 340. Method of connecting a Twin-T to obtain a bandpass amplifier.

The Twin-T can be operated as a negative feedback element in either a transistor or tube circuit. Two transistor applications are given

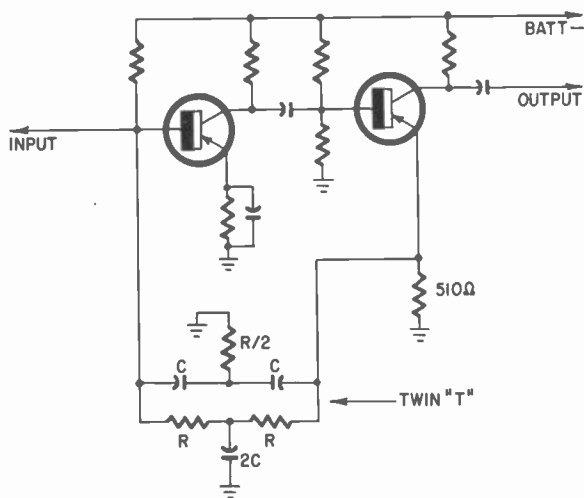


Fig. 341. Another method of connecting a Twin-T to obtain a bandpass amplifier.

in Figs. 340 and 341. In general the frequency that will be passed with the most amplification using this network is:

$$2\pi f = \frac{1}{R \times C} \text{ or } f = \frac{1}{(6.28) RC}$$

For example, let R equal 1 megohm and C equal .005  $\mu\text{f}$  then:

$$f = \frac{1}{(6.28) (1 \times 10^6) (.005 \times 10^{-6})}$$

$$= \frac{1}{(6.28) (.005)} = 31.8 \text{ cps}$$

When the source and load impedances are high, they can be neglected. Low impedances of the transistor circuits cannot be ignored as easily since they affect the bandwidth of the filter.

# pulse decoders chapter 4

There are limitations as to the number of tone channels that can be operated simultaneously on a single rf carrier. There are other methods which will permit the number of possible channels to be increased. For example, it is possible to use subcarriers — a method similar to that used for FM stereo broadcasting.

The subcarrier of, say, 100 kc is modulated with perhaps six tones. A second subcarrier of, say, 150 kc is modulated with another six tones. The radio control transmitter carrier then is modulated with these two subcarriers. In the receiving equipment, bandpass filters first separate the subcarriers, and then additional bandpass filters extract each of the six tones from each subcarrier.

This method, of course, increases the number of tone channels which can be transmitted for simultaneous and proportional control. Subcarriers of 10, 15 and 20 kc can be used, provided the tones are in still lower frequencies of 100 to 600 cycles per second.

The use of pulses will probably give the greatest flexibility and versatility in control signal applications. These pulses can be either tone or carrier types. We will consider that the normal uses such as pulse-width — pulse-spacing variations are already well known.

There are many possibilities for using high speed pulses and electronic decoding methods to obtain simultaneous and proportional control over many functions. Note that when we speak of high speed pulses we mean that pulses will be sent so fast, with respect to the equipment operation, that even though they actually are not transmitted simultaneously, as far as our equipment is concerned they will seem to be received simultaneously. The rate of pulse transmission will

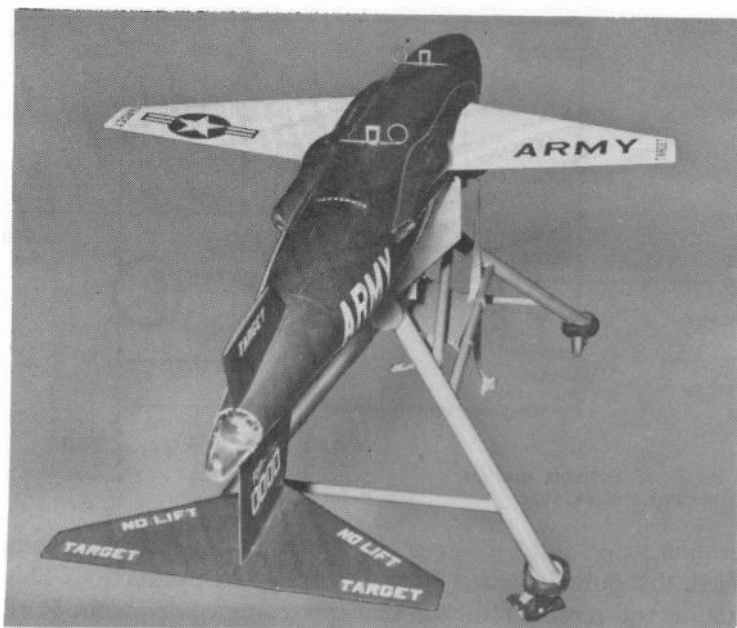


Fig. 401. Drone aircraft can be radio-controlled.

be determined by the equipment to be controlled. Fig. 401 shows a drone aircraft which could be controlled by pulse transmission. The reduced wing span and tail design is for high speed flying.

### The basic circuits

Some of the basic circuits which are used in pulse control applications are the monostable and the bistable multivibrators.

Figs. 402-a and 402-b are schematics of two types of monostable multivibrators. In Fig. 402-a, there are two possible outputs,  $e_{o1}$  and  $e_{o2}$ . Note that the emitters are connected together and have a common emitter resistor. In this circuit, Q2 is normally conducting at its

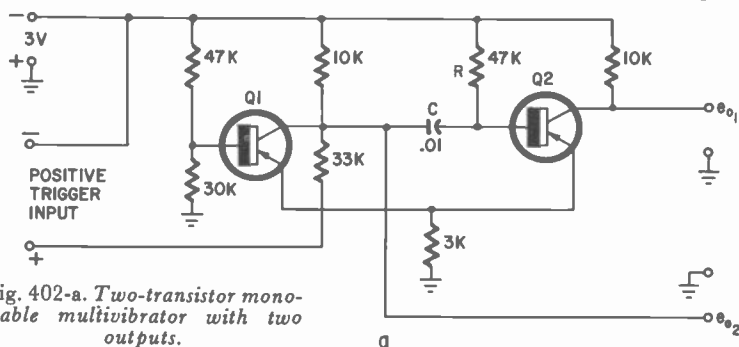


Fig. 402-a. Two-transistor monostable multivibrator with two outputs.

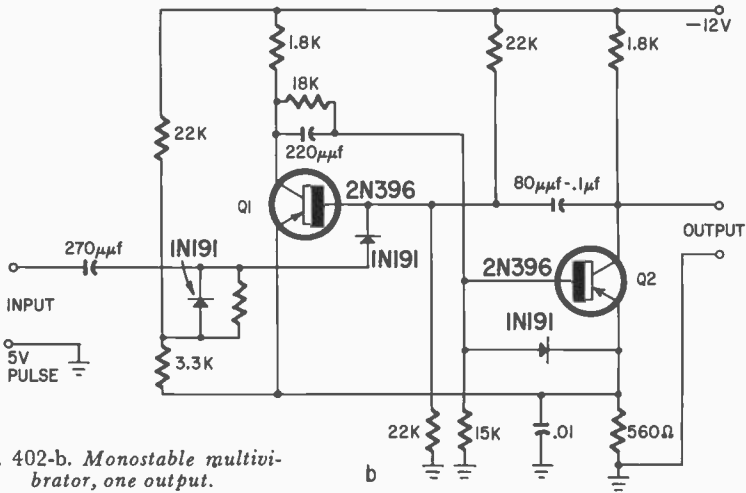


Fig. 402-b. Monostable multivibrator, one output.

saturation value and  $Q_1$  is cut off. When a positive trigger voltage is applied, this pulse is passed on to  $Q_2$  to stop its conduction. This new condition will remain until the time-governing components,  $R$  and  $C$ , restore the original conditions; then  $Q_2$  again conducts at saturation.

The trigger produces a change in the output of  $e_{o1}$  for a time duration determined by the time constant  $R-C$ . The output pulse will always be of the same amplitude and width regardless of that of the trigger so long as the trigger pulse is short in comparison with the time constant  $R-C$ .

This circuit can be used to pass on a constant pulse signal to following circuits, resetting itself each time after doing so. Since its time

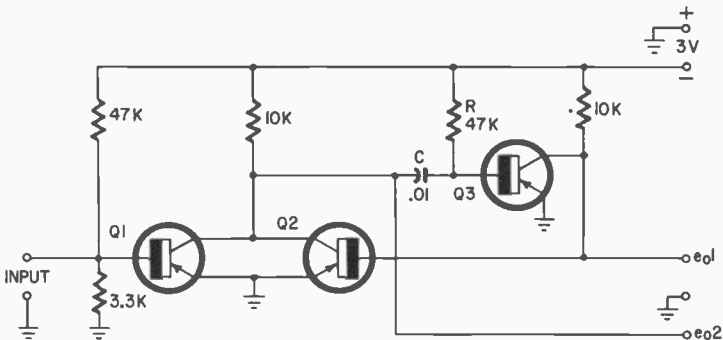


Fig. 403. Monostable multivibrator. Consider  $e_{o1}$  high amplitude and  $e_{o2}$  low amplitude. Input trigger reverses amplitudes of outputs, for time governed by  $R-C$ . Circuit then flips back to original condition.

interval can be precisely set (by varying R-C), a series of these circuits, (one energizing the other), can be used as a commutator suitable for decoding a train of pulses when the output of each is connected to one input of a coincidence circuit. Fig. 403 is another circuit for connecting transistors, this time three, in a multivibrator circuit. Fig. 404 shows typical waveforms.

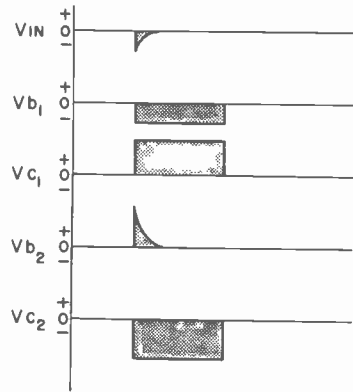


Fig. 404. Waveforms for monostable multivibrator.

Basic bistable multivibrator circuits are shown in Figs. 405-a and b. In these circuits, either transistor may start conducting first; whichever one does takes control and continues to conduct until an input pulse changes this state. The pulse required may be either positive or negative, depending upon where and when it is fed into the circuit. If we assume that Q1 starts conducting first, then a positive-pulse

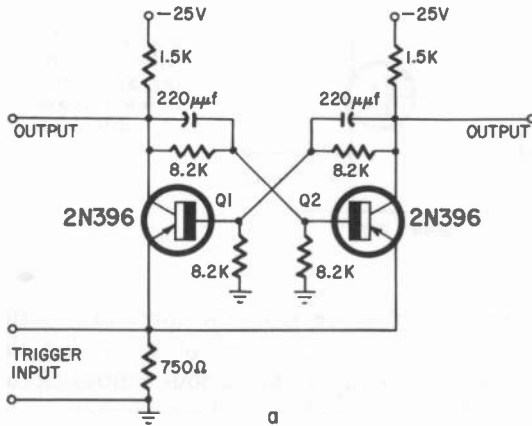


Fig. 405-a. Emitter input type bistable flip-flop multivibrator.

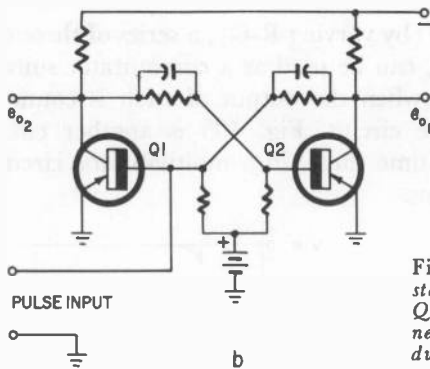


Fig. 405-b. Base input type bistable multivibrator. Initially, Q2 conducts, Q1 does not. First negative pulse makes Q1 conduct. Remains so until positive pulse stops Q1.

input would stop Q1 and start Q2 conducting. Q2 would continue conducting until a negative-pulse input was received at the base of Q1 which would cut Q2 off and turn Q1 on. Thus, there are two stable states, and different input-pulse polarities are required to change them.

This binary (ON-OFF) circuit is also used in computers and counters. It may be modified with diodes or other transistors to insure that the proper polarity input goes to the right transistor for switching, but basically they all operate in the same manner.

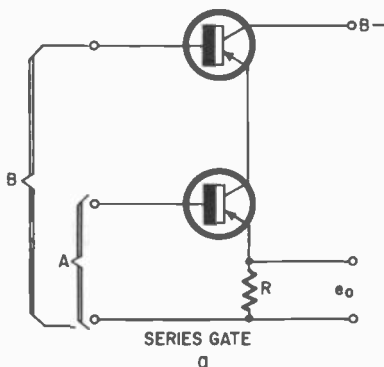


Fig. 406-a. In series gate, transistors are normally non-conducting. Simultaneous negative pulse at inputs A and B will drive transistors into conduction.

If our control intelligence is in the form of a series of pulses (a pulse train) we must have a means of separating these pulses and routing them independently to the various control circuits. This circuit can also be used as a form of pulse discriminator.

In addition to multivibrators, we can also use coincidence or gating circuits. Three basic forms of these electronic-controlled switches are given in Fig. 406.

Fig. 406-a shows the series gate. The two transistors are considered normally to be non-conducting and therefore there is no voltage developed across resistor R. To make both transistors conduct at the same time, a negative pulse must be received at the base of each (from inputs A and B) simultaneously. When these two pulses exist, then both transistors conduct and a voltage ( $e_o$ ) appears across R.

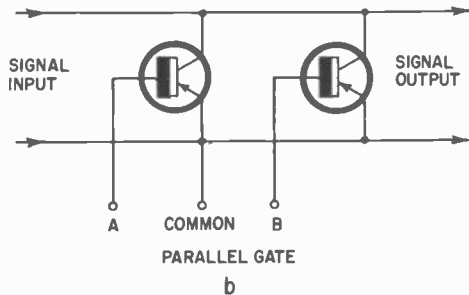


Fig. 406-b. In parallel gate, transistors conduct until a positive pulse is fed to the bases.

Fig. 406-b shows the parallel gate. Here the two transistors placed across the signal line will conduct all the time unless a positive pulse is fed to their base connections. Without a positive pulse both transistors short the line and there is no signal output until both are biased to cut off simultaneously.

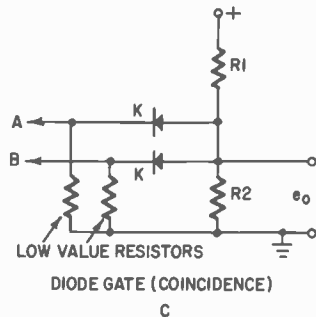


Fig. 406-c. Coincidence diode gate. Normally, the diodes short-circuit R2. If positive pulses are applied to A and B simultaneously, the diodes stop conducting and voltage  $e_o$  appears across R2.

Diodes, too, can be used for gating purposes, as shown in Fig. 406-c. In this case, two diodes are connected across R2, half a voltage divider consisting of R1 and R2. Each diode is connected and so biased that they conduct through a very low value resistor. Both effectively short circuit R2 and no output is obtained.

When positive pulses are fed to input terminals A and B, they bias the diodes and prevent conduction. This opens the short circuit across R2 and a voltage appears. Note, again, that both inputs A and B must be present simultaneously and be of the correct polarity to reverse bias the diodes.



## Fundamental concepts of high speed pulse control

Now that we have some understanding of a few circuits that can be used, let us consider how we can use a transmitted series of ten pulses. Nine of these pulses can be used for some control operation. For example, number 2 pulse will control the rudder, moving it to the right; number 3 will move the rudder to the left; number 4 will give up elevator; number 5 controls down elevator; number 6 increases motor speed; number 7 decreases motor speed, etc.

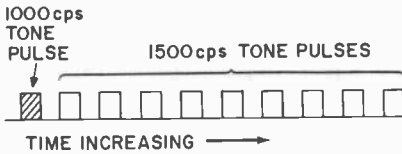


Fig. 407. A pulse "train" with "marker".

There is a reason we do not use number 1 to control a function. Number 1 will be used to identify the pulse train itself. Refer to Fig. 407. We have specified that the first pulse will be a 1,000 cycle tone; all the other pulses will be 1,500 cycle tones.

There are other ways to identify a pulse train, such as having the first pulse wider than the rest; by sending two pulses with a very close spacing compared with the rest of the pulses, or by having the first pulse narrower than the rest. The circuitry to decode such a pulse train is complicated. With two tones we can use the regular types of bandpass filters to separate the pulses more economically.

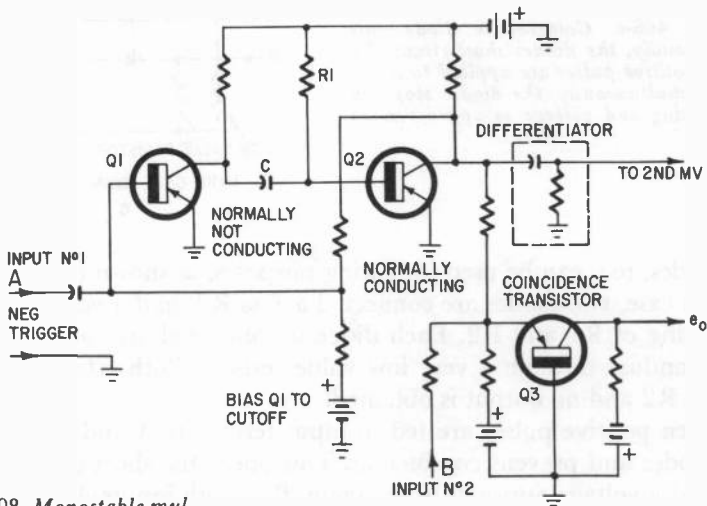


Fig. 408. Monostable multivibrator and coincidence circuit for series pulse decoding.

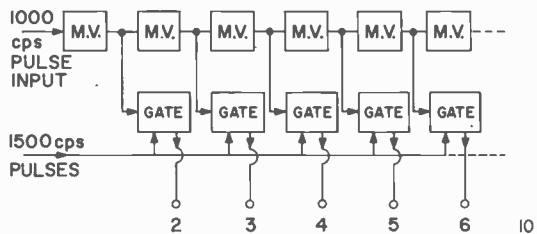
Fig. 408 is one circuit that can be used to decode a pulse sequence. This is a monostable multivibrator, a differentiating circuit and a coincidence circuit. In the coincidence circuit the transistor (Q3) conducts until both inputs (one through Q1 and Q2) have a voltage of the proper polarity to offset the bias.

The circuit operates in this manner: First the 1,000 cycle tone pulse is separated from the others by a filter, as discussed earlier. This tone pulse is then passed through a diode rectifier connected so that the output pulse is negative with respect to ground. The pulse is then applied to input A. This causes Q1 to conduct, feeding the pulse to the base of Q2 through capacitor C. This, in turn, causes the collector voltage of Q2 to rise as Q2 is cut off. The voltage at the collector of Q2 is now more negative with respect to ground and a more negative voltage is now applied to one input of Q3. This voltage alone is not enough to cut off Q3.

If the second pulse of the train arrives, is separated, rectified negatively and applied to input B, while the negative voltage from the monostable multivibrator is applied to Q3, it will cause Q3 to stop conducting. The result is a negative pulse from the collector of Q3, since the voltage at the collector rises, or perhaps we should say, increases negatively, since the p-n-p transistor requires a negative potential at its collector.

The monostable multivibrator negative pulse to Q3 is also applied to the differentiating circuit where two sharp pulses (triggers) are

Fig. 409. *Multivibrators and gates can separate control pulses.*



produced. One is positive going and the other is negative going. The differentiator circuit now feeds a second monostable multivibrator and a second gating circuit and so on down the line for nine such circuits.

Fig. 409 is a block diagram of how the circuits are combined to make a decoder. (Fig. 410 shows how small the commercially manufactured multivibrators can be.) Note that there are nine outputs, one from each gating circuit. All the multivibrators are triggered by the single 1,000 cycle marker pulse, and as this is passed down the line,

each gate is biased in turn, for its respective control pulse. When the last multivibrator is triggered, the action stops until another 1,000 cycle pulse starts the whole operation all over again.

Why do we use this? First, we could have an on-off type control. For example, suppose we wanted to send only a signal for the left rudder. We would transmit only the 1,000 cycle tone pulse and the first 1,500 cycle control pulse. This code would be sent out over and over again as long as we wanted left rudder. When the pulse appears at number 2 terminal (Fig. 409) it will bias another transistor into conduction, controlling either a servo directly or a relay.

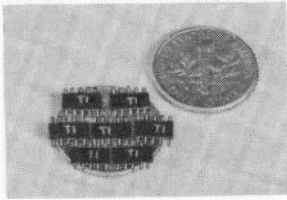


Fig. 410. Solid-state flip-flops make possible a pulse decoder [10 channels] smaller than a reed decoder. (Texas Instruments Co.)

Pulses 3 through 10 are not transmitted and we cannot send any more pulses until the same time interval has passed as would be required if all ten pulses had been sent. Thus we have to arrange, through a ground-control coder, that the pulses are transmitted automatically. In a mechanical method, a motor-driven arm can be rotated over ten contacts every revolution. The first contact would be connected to the 1,000-cycle oscillator and all other contacts to the 1,500-cycle oscillator. The arm, in turn, is connected to the transmitter modulator. As the arm rotates over these contacts, the transmitter sends out the 1,000 cycle tone pulse followed by nine 1,500 cycle tone pulses.

With control switches placed in series with each of the nine 1,500 cycle coder contacts (Fig. 411) only the closed switches will allow a pulse to be sent when the pickup arm is in that position. The coder motor speed must be adjusted so that it exactly matches the time interval required by the monostable multivibrators. In this way, each pulse arrives at its respective gate at the instant the gate is made conducting by its multivibrator.

Here is what we have gained by this method. First, if the pulse transmission rate is fast enough, the effect on the control equipment is as though they were all transmitted simultaneously. Second, there can be any combination of control functions without spillover from one channel into another. Third, control can be proportional in each channel provided the on-off control switches are replaced with another switch which would regulate whether a control pulse was sent every

revolution of the motor, or once every two revolutions or once every three revolutions.

We can thus have a control system where the control deflection is proportional to the rate of pulse arrival. For example, if we send a

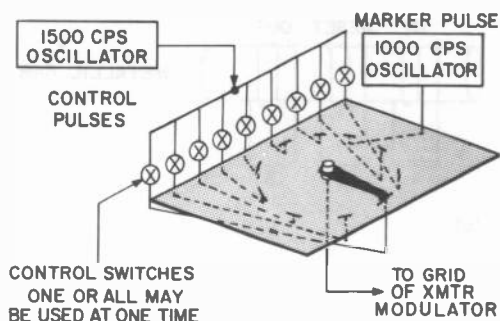


Fig. 411. A mechanical coder for pulse trains.

right rudder pulse only once every five revolutions of the coder wiper arm, this would be a small rudder deflection, while if this pulse were sent every revolution this would be full rudder deflection. As to a method of arranging the coder circuit for a variable pulse transmission rate to occur, we leave that to your ingenuity.

Summarizing then, this system can offer simultaneous control over as many channels as the coder and decoder are built to handle. Each pulse would use the full transmitter modulation and thus arrive with maximum power for the maximum range and reliability. With the small-sized components now available for use with transistors and diodes, the decoding units can be made small, light and compact.

### A pulse sorter using ferrites and transistors

We have examined one type of pulse decoder which might be suitable for simultaneous-proportional control, in which the proportional feature was obtained from how often the individual control pulses were transmitted. Now let us consider a pulse sorter that will not only separate the pulses but, in addition, will preserve the width of the control pulse. This makes it possible to use width variation to obtain proportional control.

With this system, the pulses as well as the spaces between them are in microseconds — truly a high speed system when compared to more common radio control methods. All other characteristics concerning the unlimited number of channels, etc., apply.

Before going into the circuit proper, we must understand the operation of an additional circuit element that is used, the ferrite core. Refer to Fig. 412-a in which a linear core is shown with three windings. Also shown (in Fig. 412-b) is a magnetic core hysteresis curve.

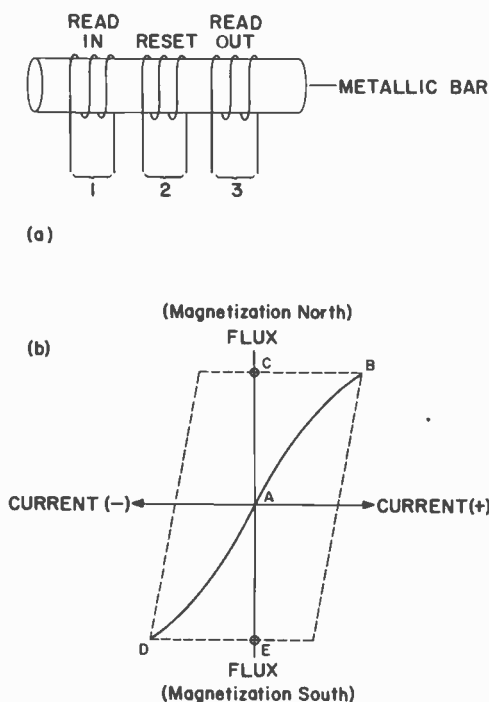


Fig. 412. Three-winding coil with ferrite core [a] and magnetic core hysteresis curve [b].

The core can be magnetized in either direction and, once magnetized in a given direction, will hold this magnetization until a reverse current flow reverses the magnetic polarity.

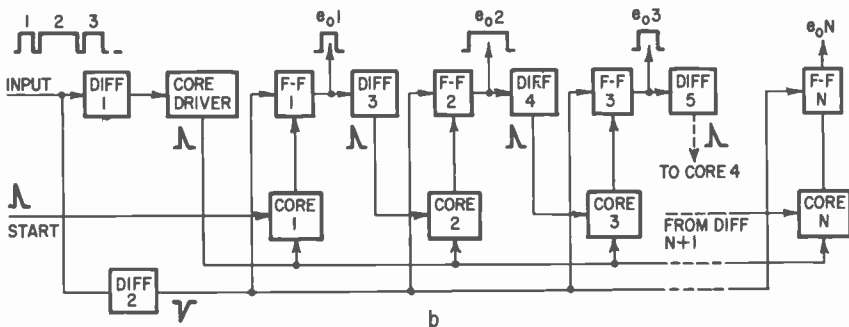
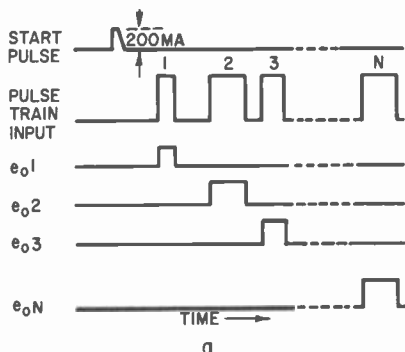
On the hysteresis loop, Fig. 412-b, point A represents the initial condition of the core, when it is not magnetized in either direction. The curve A to B indicates that a current is flowing through, say, the read-in winding. Note that the flux reaches a maximum at point B. The current then decreases to zero but the bar remains magnetized north (point C). It remains in this condition although no current flows in any winding.

Suppose that some time later the reset winding is energized with a

current which flows in a direction opposite to that of the first. Again, on the curve, as the current starts to build up (on the negative side of the current axis in Fig. 412-b), the flux first remains the same, then suddenly drops to point D. This drop means that the molecules in the core are now reversed. The end which was north is now south. Again the current decreases to zero and the bar is magnetized (E) in this new direction (south).

A meter placed across the read-out winding during this flux reversal would have given a quick jump of its pointer. If we send in another reset pulse, we will not get a read-out pulse because the core magnetism does not change. If, however, we feed in a read-in pulse, we do

Fig. 413. Block diagram of pulse sorter. Width of each pulse [drawing a] sent into sorter is reproduced at outputs  $e$ . Last output  $e_{0N}$  [drawing b] of sorter can be used to pulse core 1, thus setting up the sorter for the next pulse train. Differentiators 3, 4 and 5 set up cores for pulse from core driver. [Electronics Magazine.]



have a flux reversal and a read-out pulse is produced. We will get a positive-going pulse when, for example, we send a read-in pulse and a negative-going pulse when we send a reset pulse. The circuitry following such a core can use either one or the other or both of these output pulses, depending on the application. Although we have shown a bar or rod in this example, the core is normally circular, a donut or toroid which has a very high permeability and is capable of a large flux change in spite of its tiny size.

Fig. 413 is a block diagram of the ferrite core system. The start pulse sets the sorter to receive the pulse train, as in the previous decoder. This pulse switches ferrite core number 1 OFF, which turns off transistor flip flop (another name for a multivibrator) number 1 (F-F1). The leading edge of the first input pulse is shaped into a positive pulse by differentiator number 1 which then pulses the core driver. The output of the core driver switches core number 1 ON which then feeds a positive pulse to flip flop number 1. Flip flop number 1 (which sorts out the first pulse of the train), is now pulsed into its ON condition.

The trailing edge of the first input pulse is shaped into a negative pulse by differentiator number 2 which is fed, in turn, to flip flop number 1. Flip flop number 1 then goes OFF and thus has duplicated the first pulse of the train.

When flip flop number 1 went ON, it fed a negative pulse to differentiator 3 setting up core 2 for the next input pulse of the train in the same way as the start-pulse prepared core 1 for the first input pulse. Flip flop number 2 and the following flip flops form symmetrical pulses from the following pulses at their outputs the same way that flip flop number 1 did.

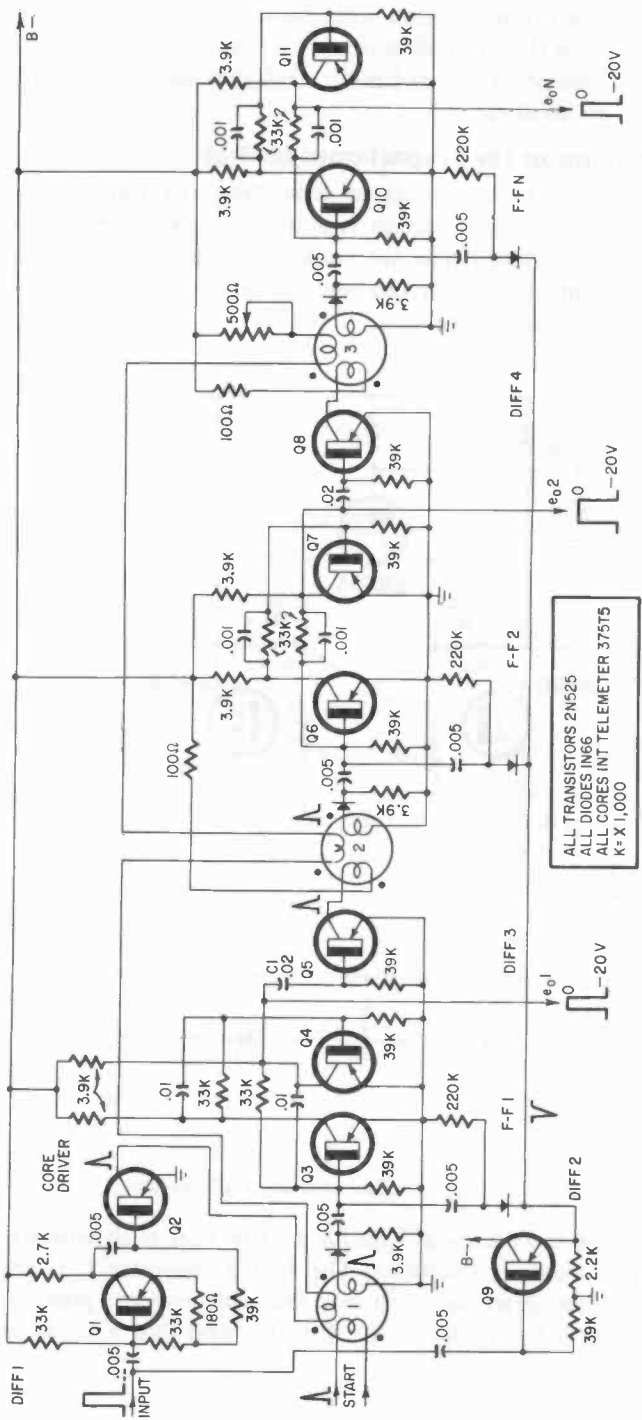
### Circuit details

In Fig. 414 Q1 and Q2 feed 200 ma pulses to the cores. For core read-in 2 ampere turns are required, and for a margin of safety, each core is wound with 12 turns. About 0.5 volt is produced by each turn of the output winding, and each flip flop transistor, such as Q3, requires a trigger pulse of 2 volts. For a safety margin, the core output winding has 5 turns. The reset winding, like the read-in, requires 2 ampere turns. It also has 12 turns.

The 200 ma reset pulses are produced by the flip flop output stages. An output stage transistor with a nominal beta of 40 requires 5 ma for its base circuit from its flip flop to produce the 200 ma pulse. This is the reason for the large value of C1.

The transistors such as Q2 and Q5 that drive cores are biased so that only the collector cutoff current, about 5 microamperes, flows between pulses. Thus the drivers appear as impedances of at least 1 megohm.

The flip flops are turned off and on by positive and negative triggers, respectively. Positive triggers have low amplitudes. Negative triggers turn on the flip flops when the pulse level rises above a well defined threshold level. These negative trigger pulses are supplied by Q9. Each flip flop delivers a positive going pulse for an output.



ALL TRANSISTORS 2N525  
 ALL DIODES 1N66  
 ALL CORES INTI TELEMETER 37515  
 K = X 1,000

Fig. 414. Circuit of pulse sorter. [Electronics Magazine]



Cores can be scramble wound with No. 28 or 30 Formex wire. The windings are all in the same direction, and concentrated in three areas of the core. These cores do not function reliably above 60° Centigrade (about 140° Fahrenheit.)

### Pulse discriminator for proportional control

We have covered some ways of separating the pulses in a pulse train and we have given a circuit which will preserve the input pulse widths. It was suggested that we could use this width variation for proportional control of each channel. Now we want to consider a possible method of doing so.

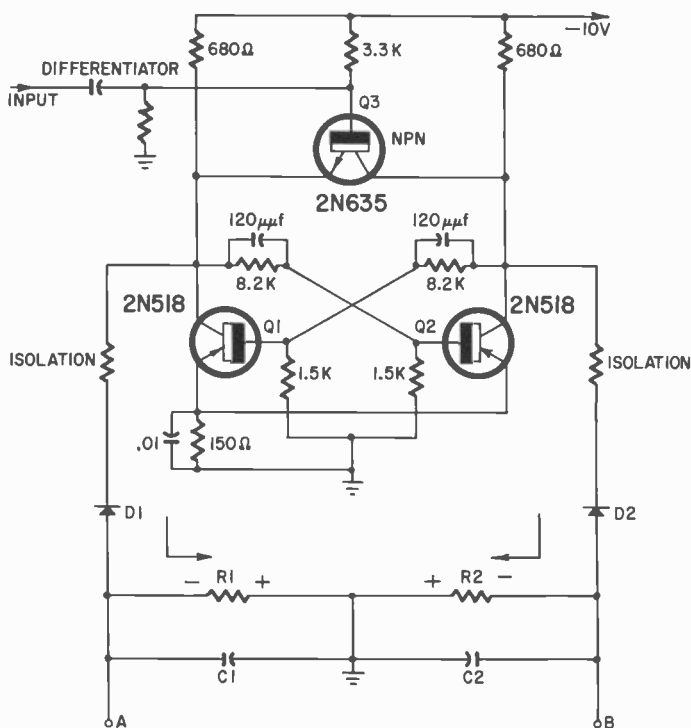


Fig. 415. Pulse discriminator and multivibrator.

Fig. 415 is a conventional bistable or flip flop multivibrator schematic with two circuit additions. The first is transistor Q3, an n-p-n type which is connected in a manner that will insure a positive input pulse will trigger the circuit in one direction and that a negative pulse

will trigger it in the reverse direction. Added components are the two diodes, D1 and D2, R1 and R2, and C1 and C2.

For the theory of operation, assume that its input is the output of Fig. 414. Let this square wave output be  $e_{o1}$ :

If this particular channel has a symmetrical output pulse (a pulse whose spacing is equal to its width) and if it feeds the differentiator shown in Fig. 415, it would have the waveforms shown in Fig. 416.

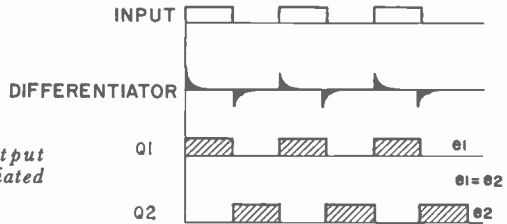


Fig. 416. Symmetrical output pulses and their differentiated waveforms.

WAVEFORMS FROM DIFFERENTIATOR AND OUTPUT PULSES FROM BISTABLE M.V.

The positive differentiated spike turns on Q1 while the negative spike turns on Q2. Since the pulse widths and spacings are equal, each transistor (Q1 and Q2) are on the same amount of time.

Whenever Q1 is cut off, its collector voltage rises. A current will flow through D1 to R1-C1, as indicated by the arrow. The same would be true for Q2. Now, since the pulse widths and spacings are equal, the currents through R1-R2 are equal but in the opposite direction, thus the output across A and B is zero. Capacitors C1 and C2 are needed to store the voltage drops momentarily during the time when the collector voltages drop. Two isolation resistors are used to prevent any possible interaction between the R-C filters and the multivibrator time constant components.

The input pulse width in Fig. 417 has increased and the spacing decreased. The differentiated spikes are no longer symmetrical. Q1

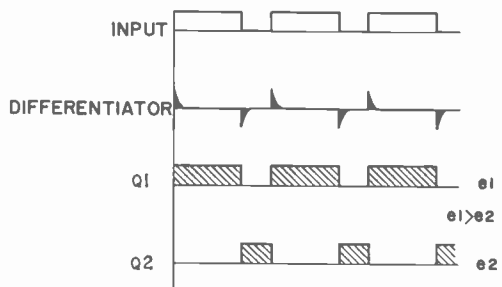


Fig. 417. Effect of pulse width wider than spacing.

remains cut off longer than Q2. Therefore the voltage delivered to R2-C2 is longer and thus becomes higher in amplitude than that from Q1. This unbalances the output and point A in Fig. 415 will be positive with respect to point B. The actual voltage produced would be proportional to the pulse width unbalance.

Fig. 418 shows the reverse situation, where the input pulse width is narrower than the spacing. This unbalance is in the opposite direc-

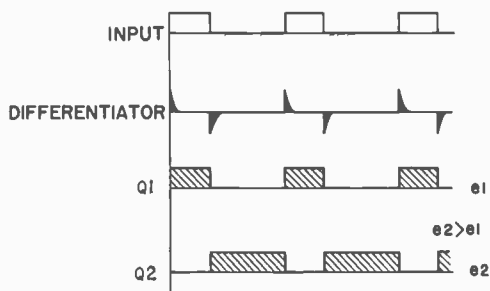


Fig. 418. Effect of spacing wider than pulse width.

tion and point A becomes negative with respect to point B. Again the actual voltage produced would be proportional to the unbalance in pulse width and spacing.

By varying the pulse width and spacing in a train of ten pulses, we can command a change of direction by a change of voltage polarity, and the degree of change by the amount of either the positive or negative voltage.

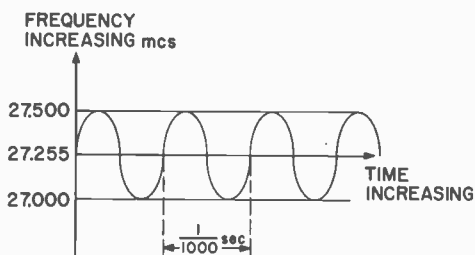


Fig. 419. The frequency-modulation concept.

### Simultaneous transmission of pulse rates

Another method of obtaining proportional control through pulses is to transmit several pulse rates simultaneously. If we were to have four tones, and each capable of being pulsed at a varying rate (spacing and width constant), we would have the basis for proportional and simultaneous control over four functions. This would mean there would have to be four bandpass filters to separate the four channels.

We will have to transmit four tones simultaneously, however. This will mean a little more amplification after each filter to get sufficient tone strength. The rates can then be averaged in a simple diode counting circuit which would produce a voltage proportional to the pulse rate to serve as a basis for proportional control of many functions.

### Frequency modulation of a pulse repetition rate

Another possibility is that of using frequency modulation techniques combined with pulses to achieve control. This idea would help maintain the strong modulation characteristics we desire.

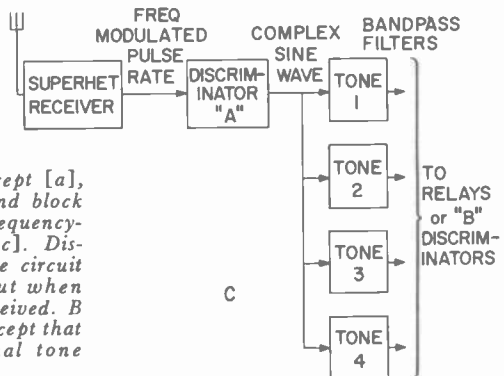
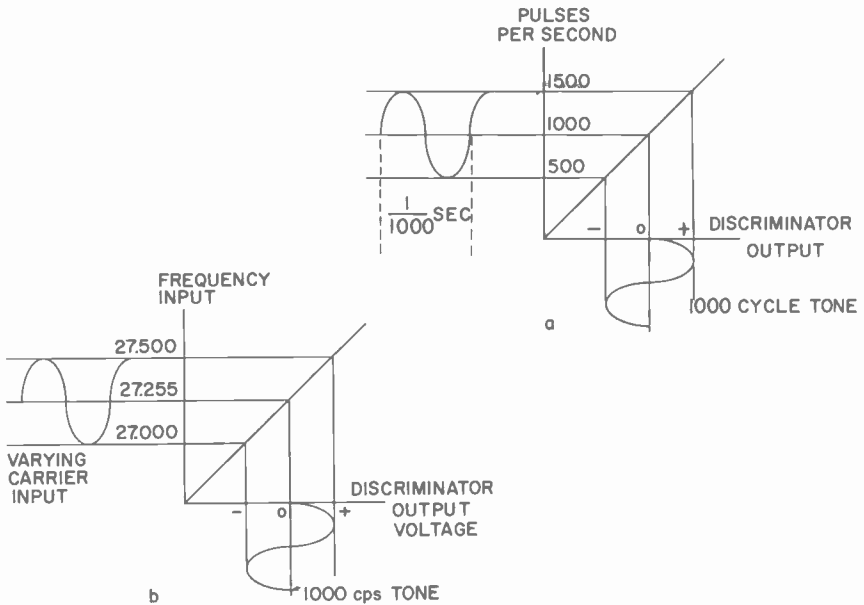


Fig. 420. The FM pulse concept [a], FM receiver operation [b] and block diagram of system decoding frequency-modulated pulse-rate code [c]. Discriminator A is an audio type circuit designed to have zero output when pulse resting frequency is received. B discriminator is similar to A except that it is designed for individual tone frequencies.

Review, for a moment, the concept of frequency modulation. When we frequency modulate a carrier, we make the carrier go higher, then lower, than the resting (center) frequency at the desired tone rate. Fig. 419 shows this concept as applied to a 27.255 mc rest frequency when modulated with a 1,000 cycle tone. Note that the carrier is changed by the 1,000 cycle sine wave in a sinusoidal manner from 27.255 to 27.500 back to 27.255, down to 27.000 and back to 27.255 mc at a 1,000 times per second rate.

What the FM receiver does when it picks up this varying wave is shown in Figs. 420-a-b. Note that the varying carrier goes in, on the left, and comes out on the bottom as a 1,000 cycle per second positive and negative voltage variation. This voltage variation is the modulation tone at the transmitter.

We cannot frequency modulate the carrier on any of the radio control frequencies which the FCC has allocated for radio control since these are spot frequencies. We can, however, utilize this principle by frequency modulating a pulse rate to obtain simultaneous transmission of many control signals. The possible receiver action is indicated in Fig. 420-c. Note that we would apply the pulses to a tone type frequency discriminator and as an output get the tone causing the pulse rate variation.

It is interesting to note that when transmitting pulses (if the pulses are applied to a transformer or to an R-C network) we can recover a cycle for each pulse. In this case then, the frequency modulated pulses, when applied to a discriminator, would produce an output tone which would be exactly identical with the tone causing the pulse frequency modulation.

If we were to modulate these pulses with a combination of four different tones, we would recover a complex wave with a pulse discriminator. This wave could then be broken down and the individual tones separated by bandpass filters.

## Two useful pulse shapers

Two simple pulse shaping circuits are given in Figs. 421 and 422. In Fig. 421 an input drives the transistor to saturation and to cut off. This could be a trigger type input. Capacitor C is charged rapidly through D1 and discharges slowly through D2 into load R. Thus a square wave is produced from a trigger input.

In Fig. 422, a sine wave is rectified by diode D1 and applied, in the correct polarity, to the n-p-n transistor Q1. The output of Q1 is amplified by Q2 which is driven to saturation and cut off to produce the square wave pulses shown. If the sine wave input to D1 were to

constantly change slightly in frequency, the pulse output of Q2 would be pulses frequency modulated, in a like manner.

**Mechanical decoder pulse control system**

Decoders for pulse command work seem limited only by the imagination and the mechanical and electronic systems used. This mechani-

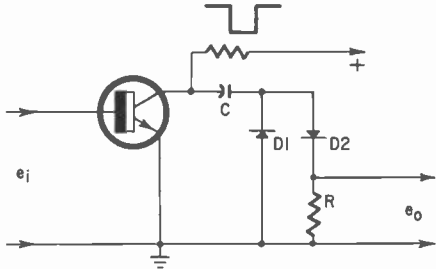


Fig. 421. Pulse shaping circuit. This circuit produces square waves.

cal decoding and control system was developed to obtain control over the rudder (proportional steering), the elevator (trim) and the motor of a model aircraft engine. The system uses but one channel with the pulse-width — pulse-spacing variation type of command-code modulation.

The concept of rudder steering used in this code is well known, and it will be assumed that the reader understands this method of control.

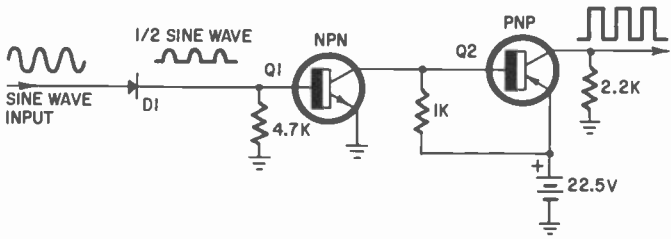


Fig. 422. Pulses produced from sine wave [tone].

The elevator operating code derived from this is: Carrier on solid, no pulsing equals up-trim; carrier off, no signal, equals down-trim. The engine control circuit code is a mixture of a full-on command, followed immediately by a full-off command, after which pulsing may be resumed. A fail safe provision is provided by mechanical elevator stops which prevent the model from going into a dive in case of loss of signal.

The basic system is shown in Fig. 423 and is constructed around a single Mighty Midget motor and its integral gearing and gear shaft. Note that in this drawing, which illustrates the rudder and elevator

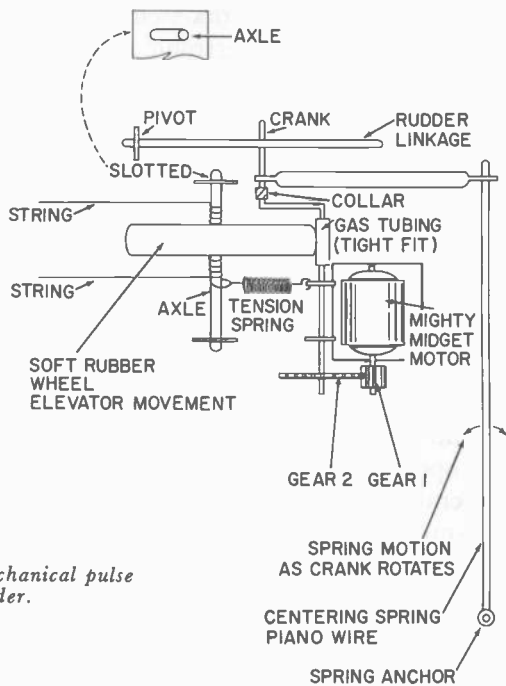


Fig. 423. *A mechanical pulse decoder.*

control mechanisms, the large gear shaft has been bent into a crank, and that there is a piece of aluminum tubing connected to the crank by one flattened end and to a piano wire spring at the other. The spring and the tubing center the rudder. A piece of gas-line tubing has been placed on the gear shaft so that it provides a friction drive for the soft rubber elevator-movement wheel. Note also that the elevator-movement wheel axle is set at the bottom into a good tight bearing fit, while at the top, the axle is slotted so that it can be pulled to the left far enough so it will not touch the gas-line tubing on the gear shaft. Next locate the tension spring just below the elevator-movement wheel; this spring normally holds the wheel against the gas-line tubing so that a good friction drive is produced.

Fig. 424 shows how the rudder is connected through strings to the steering-control mechanism. The circle indicates the path of the tip of the rudder crank if it were to rotate freely. The dotted linkage is the centering tubing described previously. Fig. 424-a shows the rudder

linkage in the neutral position. The crank will oscillate back and forth from this neutral position when equal width pulses and spaces are received. In Fig. 424-b the rudder crank is displaced from center by a code of unequal width pulses and spaces; the rudder-linkage bar is moved as shown, and the rudder is deflected.

In most applications for this type of pulse control, a centering spring is connected to the crank itself and pulls the crank back to neutral. In this case, the maximum restoring force occurs at somewhat less than 90° crank displacement, when the line of action is perpendicular to the crank position. With the spring arrangement shown, with the force ahead of the crank, the maximum torque will not occur until

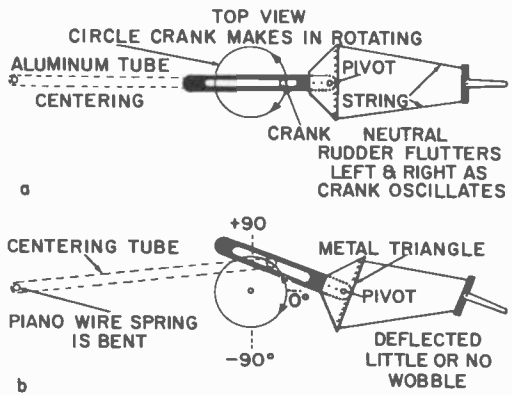


Fig. 424. Rudder is connected by strings to steering-control mechanism. Crank must be able to rotate. Must also have some spring tension at neutral.

somewhat after the 90° crank position and thus the system is more linear near the ends of the swing. This means a larger deflection of the rudder is possible under normal operating conditions. Because of the slotted bar the crank can oscillate at the extreme positions and will not impart any motion (wobble) to the rudder itself. Actually the wobble gets smaller as the crank moves further from neutral.

As long as only a rudder-control operation is desired, the crank oscillates between the plus 90° and minus 90° positions. It does not turn through a revolution. But suppose we want to change the elevator trim. If we hold the signal on the crank will now rotate. The rudder will wobble, but its dwell time on each side of center will be the same so there is no change in model direction. What does happen, however, is that the rubber wheel (Fig. 423) which is now touching the gas-line tubing is turned. The elevator, connected to the axle of the rubber wheel through two lengths of string or cord, is moved into a new position as the string on one side of the rubber wheel tightens and that on the opposite side loosens by the same amount. As soon as the desired elevator trim is achieved, the constant signal is stopped and the pulse



signal resumes, and the control crank returns to oscillate about its neutral position. Note that to change the elevator trim in the opposite direction we would merely cut off the signal until the desired trim was obtained and then resume pulsing again.

Now here's the reason for the slotted bearing at one end of the elevator wheel axle. Since we have provided physical stops to prevent

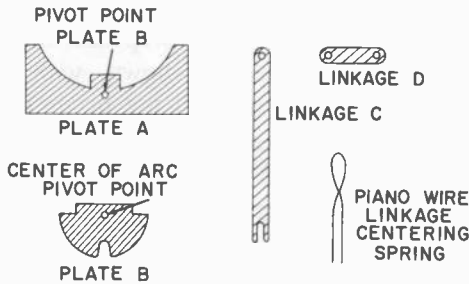


Fig. 425. Parts required for motor control. Use thin aluminum pieces.

the control surface from moving too far from neutral, we must also have some means of stopping the rubber wheel to prevent breaking the string, or at least smoothing the friction surface. Note, then, how the elevator wheel motion is stopped when the limit is reached. The string

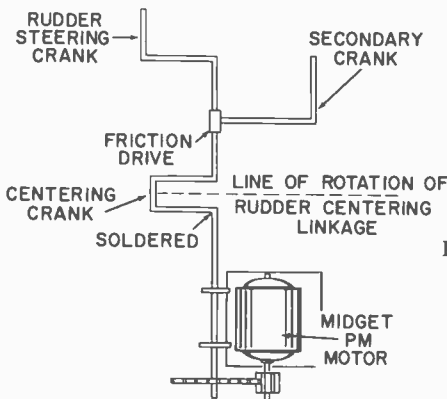


Fig. 426. Details of secondary crank addition.

on the one side will continue to tighten. As it does so, it pulls the elevator-wheel axle which slides in its top bearing slot away from the gas-line tubing. A continued signal for still more elevator deflection will have no effect. Now, if we want to reverse the crank direction to return the elevator to its original position the tension spring will pull the

elevator wheel shaft tight against the gas-line tubing so that the friction drive is re-established.

Since the elevator wheel is large compared to its axle, a very gradual control of the elevator is possible. One revolution of the axle will wind up only a very small amount of string. By changing the diameter of the wheel and the axle roller, the speed of elevator movement can be changed.

The final portion of the mechanism is a little more complicated. First, examine Fig. 425 which shows the parts required. These five parts are not to scale and must be custom made for each system. Now examine Fig. 426 which shows modifications to the gear shaft. A U-section is added as shown, and a second crank (secondary crank) is added. This secondary crank is so connected to the gear shaft that it is tight enough to hold a position while the gear shaft rotates when desired.

Next refer to Fig. 427 which shows how the five parts of Fig. 425 are assembled. Plate B is pivoted to plate A and is free to rock back and

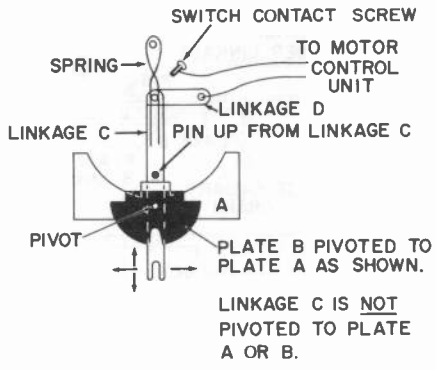


Fig. 427. Assembly of switch parts.

forth. Linkage C is positioned so that its pivot to linkage D is directly above the pivot connecting A and B. Linkage D is then pivoted at its other end to a base plate. The spring is adjusted so that it will hold linkage C in the position shown and keep the pin in linkage C against the center square of plate A as shown. Linkage C should move easily left or right under plate A or up and down as shown by the arrows at the lower end of Fig. 427. The anchor pivot for D should be tight enough so that both linkages do not have any end play, yet is free enough to allow easy pivoting.

The same arrangement is shown in Fig. 428, and a circle indicating the rotary motion of the rudder steering crank has been added. Note that the secondary crank is inserted in the slot of plate B. When the rudder crank is in the neutral position, it is exactly opposite the slot in plate B.

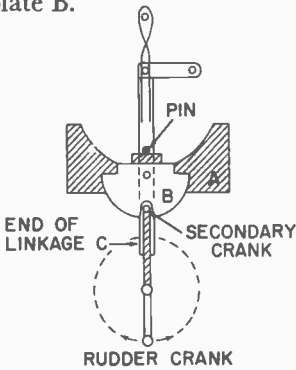


Fig. 428. Position of primary and secondary cranks in normal operation.

Fig. 429 is a simplified side view of the mechanism assembled with the other components. The only change is that linkage C is placed above plates A and B, and its pin goes down as shown.

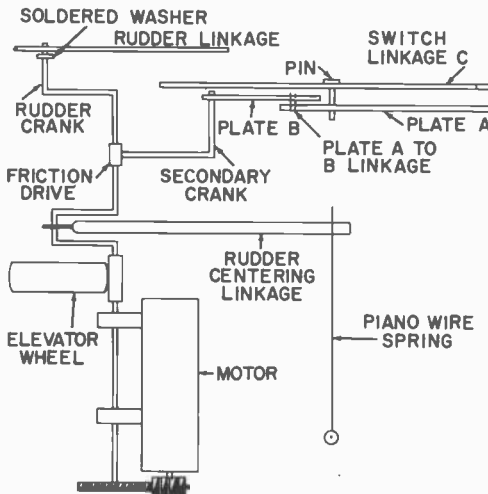


Fig. 429. Side view details of mounting. Rudder crank engages end of linkage A during rotation.

Now see Fig. 430 for the operation. With the secondary crank inserted in the slot of plate B and the rudder crank exactly opposite (Fig. 430-a), we start the system by sending control pulses. The rudder crank can move back and forth as required for steering and plate B will oscillate back and forth also. Steering is perfectly normal.

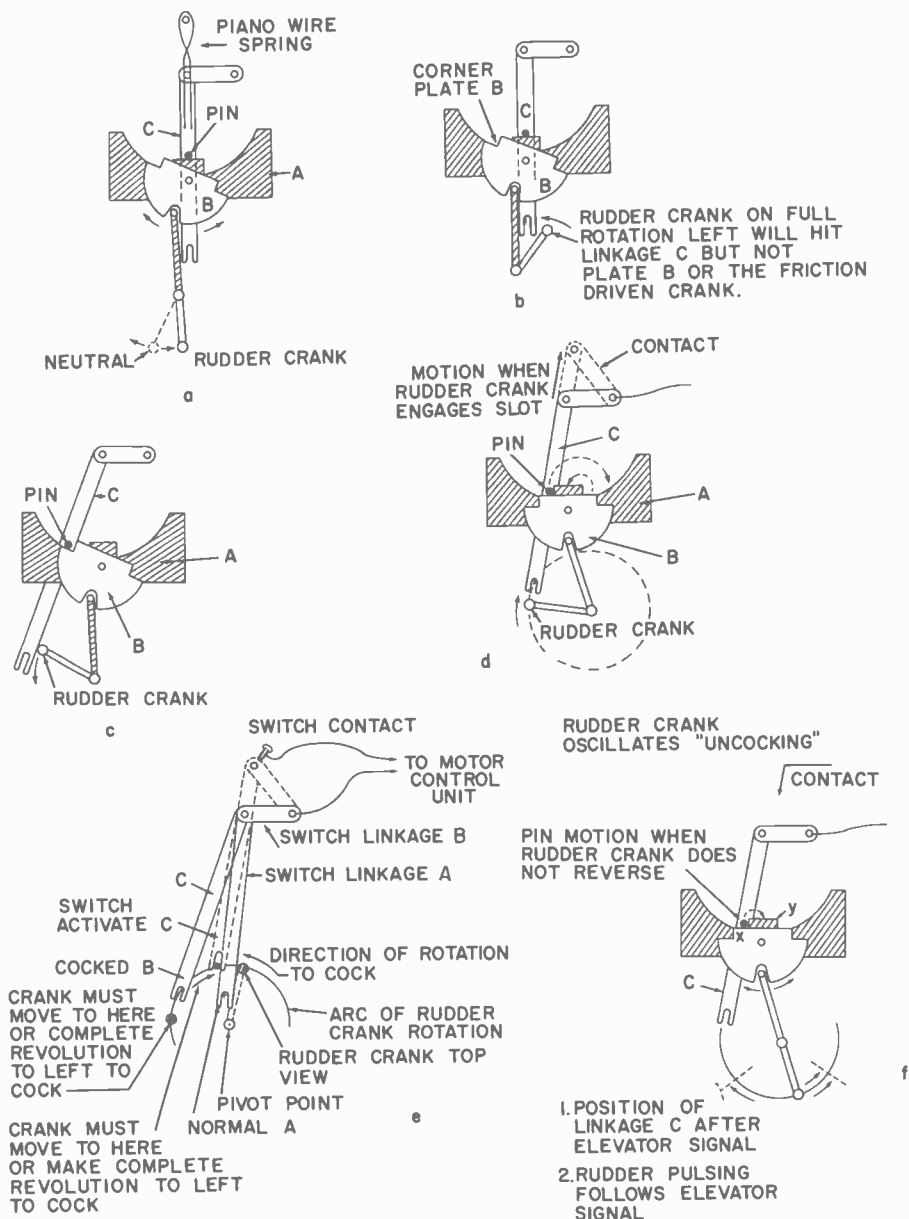


Fig. 430. Plate B oscillates [drawing a] as rudder crank oscillates. Linkage C remains in position shown. Plate B [drawing b] is restricted from moving further by mechanical stop. Friction drive to secondary crank allows it to stop while motor keeps turning rudder crank. Rudder crank [drawing c] moves linkage A so pin drops into B-plate indent "cocked position". Note that pin will move to the right after crank passes so slot in A will rest on crank circle. If rudder crank [drawing d] immediately reverses, it engages slot, pushing C up as it goes "firing" [linkage C touches contact]. Drawing e shows the movement of linkage C. When plate B oscillates [drawing f] as the rudder oscillates, shoulder X rises to move pin to Y. Linkage A does not move back to take contact.

In Fig. 430-b an ON signal starts the rudder crank motion. Plate B is pushed to the left until its corner rises level with the square midsection of plate A. It is held there by means of a mechanical pin stop (which, for simplicity, we have not shown).

Remember that the crank which moves this plate is friction connected in the gear axle. The rudder crank then continues to rotate as shown in Fig. 430-c and as it does so, it hits linkage C and moves it over until its pin drops in the corner of plate B. The spring pushing down locks it in this position. The rudder crank keeps going but linkage C now remains in this deflected position. Note that after the rudder crank passes linkage C in its locking-in position, the linkage settles so that its slot is directly in line with the rudder crank circle of rotation. If we now send an off signal and hold this momentarily, the rudder crank reverses its rotation (Fig. 430-d). As it does so, the rudder crank moves into the slot at the end of linkage C and forces it back and up until it closes the contact placed as shown in Figs. 430-e and f (an adjustable screw contact is shown; this could be a spring-type contact so it can bend). As the rudder crank continues its rotation, linkage C is moved over to the right position where it slides down the circle of plate A to come to rest against the square center of plate B which has also moved to the right. It will remain there even though the rudder crank continues to rotate for a second or so longer.

Now assume that we resume sending the pulse signal. Immediately plate B starts to oscillate and as it swings to the right, its corner pushes the pin on linkage C, moving it up high enough to slide onto the square center section of plate A. Due to the spring tension the linkages return to their neutral positions and everything is back to normal again.

If an elevator signal is now transmitted the contact will not be closed unless we send an up elevator signal and follow it immediately with a down elevator signal. If pulsing starts, even for a second, between up and down elevator signals, the motor control contact mechanism will uncock and will not make connection to the motor control unit.

We can send elevator signals, then, without this part of the unit being affected. Should we send an engine speed-change signal (and remember, this must be an ON signal followed immediately by an OFF signal), the elevator is hardly affected since the length of time required to cause the engine change is extremely short. Actually, we only require one revolution of the rudder crank in one direction and then an immediate reverse back to neutral. The elevator control string won't wind since the two rotations are equal.

# design and operation of proportional control servomechanisms

## chapter 5

The true servomechanism is generally recognized to be similar to that outlined in Fig. 501. Its operation is basically that an input signal

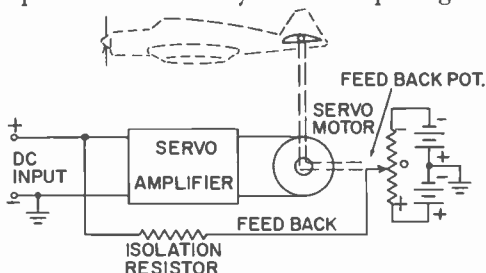


Fig. 501. A true servomechanism.

will be strengthened in the servo amplifier and produce enough output power to operate the servo. When the servo motor (in this case) runs, it not only moves the controlled element (elevator, as shown, or rudder) but it also moves a feedback-potentiometer wiper arm a proportional amount.

There is an electrical connection between the wiper arm and the servo amplifier, and an electrical signal is fed back to the amplifier to report the position of the control surface. This feedback is used to balance the input signal in one way or another. When the feedback signal has neutralized the control signal the servo motor comes to a stop. Any new signal fed to the servo amplifier must unbalance the zero movement signal condition existing in the amplifier. The polarity

(or phase) of the input signal in relation to that of the feedback signal will determine the direction in which the servo will drive the control surface. For example, assume that the signal input is +2 volts with respect to ground. The servo amplifier strengthens this signal, converts it to a current output which causes the motor to run clockwise. When the motor runs it tilts the elevator control surface up, and it also moves the wiper arm of the potentiometer nearer to the negative end of the resistance. This negative voltage feedback to the input cancels the input signal when the elevator is tilted, say,  $10^\circ$ . The elevator will remain deflected this amount as long as we keep sending the signal which produced the +2-volt input.

Now assume we stop sending this signal. Immediately the +2-volt signal at the input of the servo amplifier vanishes. All that remains is a -2-volt potential from the feedback potentiometer. This negative signal causes the motor to run in the opposite direction, moving the elevator control surface back toward neutral, and at the same time moves the feedback potentiometer wiper arm toward the center of the resistance.

When the potentiometer wiper arm is exactly centered there is no voltage difference between this point and the center tap of the batteries; thus there is no longer any negative voltage being sent to the amplifier input. The motor stops and the servo is neutralized. This is a self-neutralizing type of proportional control servo. In the absence of any control signal input, the motor will always return the wiper arm to this point of zero feedback voltage.

It is interesting to note that the servomechanism is actually an active element in itself. It can exhibit some peculiar characteristics without any help from the rest of the control system. For example, it can act just like a tuned circuit, and it does have a resonant frequency. When improperly designed it can oscillate gently or violently.

The sensitivity of the servomechanism is dependent directly upon the amount of gain of the servo amplifier. By sensitivity we mean its ability to position precisely the surface it controls. The more gain the amplifier has the smaller the input signal can be and still produce motor movement. Also, the more exact the cancellation of the input signal has to be through the feedback voltage.

Low amplifier gain, on the other hand, requires a much larger input signal and has less exact signal cancellation. For example, in a low gain system, the motor might not run until the input signal exceeds 0.5 volt. When the feedback cancels the input, it can cancel down to 0.5 volt. The motor stops running but the control surface, instead of

being positioned to exactly  $10^\circ$  as commanded, might have been moved only  $8^\circ$ . By increasing the amplifier sensitivity so that the motor runs with a signal of .1-volt unbalance, then the positioning will be more exact — about  $9.6^\circ$ .

High amplifier gain, then, is needed for more exact control surface positioning. Amplifier gain that is too high can cause oscillation. The mass, and thus inertia, of the motor is one reason for oscillation. For example, with a +1-volt signal, a servo amplifier gain can be so high that cancellation down to .01 volt is required to stop motor rotation. Now, with the +1-volt signal applied, the amplifier sends a large amount of power to the motor. It rapidly drives the wiper arm and control surface toward the -1-volt position on the feedback potentiometer. Because of the inertia of the motor it actually overshoots this

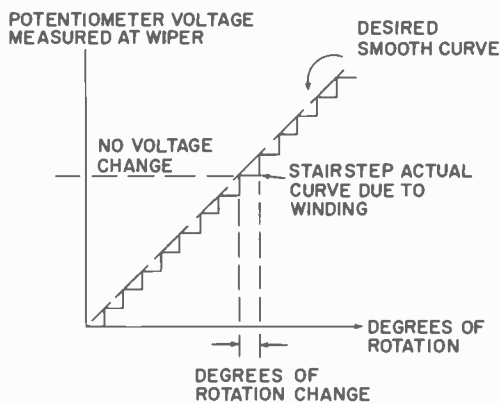


Fig. 502. Stairstep voltage output of potentiometer.

position. Instead of exactly cancelling the input signal the feedback signal reaches a value of, say, -1.2 volts. This -0.2-volt difference in signal causes the motor to reverse. Again it overshoots due to inertia. And so it oscillates about this -1-volt feedback signal position. The oscillation may last a long time or a short time, depending on the amount of damping such as friction in the motor bearings, potentiometer arm shaft, etc. Thus, in a servomechanism, the right amount of gain is needed for fast, accurate positioning but not so much gain that we get oscillation.

There is another factor we should mention regarding the exact positioning and that concerns the fineness or resolution of the feedback potentiometer itself. Remember, if a wire-wound potentiometer is used, there is a voltage jump between each turn the wiper arm rests on. The voltage output is not precisely smooth but varies in a stair-step fashion, as shown in Fig. 502. Because of this stair-step situation the voltage changes in jumps. This, too, can cause oscillation. When



the amplifier gain is excessive the feedback may never be able to cancel the input exactly.

The amount of voltage across the feedback potentiometer is independently important. It is possible, by regulating the amount of this voltage, to establish a servomechanism gearing ratio. For example, we can set the feedback voltage so that 0.5 volt is produced for, say,  $4^\circ$  of potentiometer wiper arm rotation. (This is the equivalent of saying that a 0.5-volt input is equal to  $4^\circ$  fin deflection, assuming complete signal cancellation during operation.)

Now suppose we want to get a larger fin deflection for the same input signal. If we reduce the voltage across the feedback potentiometer so that it produces 0.5 volt for  $8^\circ$  potentiometer wiper arm rotation, we now will get this increased deflection. All we changed was the voltage across the feedback potentiometer. To decrease the deflection, we increase the voltage.

This can be put to use when trying a new system with a small deflection of the control surface (to start with) as a requirement. Later we can increase the voltage across the potentiometer to get the amount of deflection needed for stunting, etc.

Let us go back now to the concept of motor mass and inertia. Of course the gears and fin also have mass and thus inertia. We will assume that all masses can be lumped into one and we will call this amount of inertia ( $I$ ).

Friction in the system can reduce or prevent the output shaft from oscillating. Damping can be provided by means other than friction. For example, we can connect a 10- to 50-ohm resistor across the motor leads. When the relay causing the motor to run opens, the motor armature winding produces a current (while the motor is coasting) which finds a path through this resistor. Due to this current, the armature now becomes a magnet and because the field poles are magnets, there is an immediate drag which makes the motor slow down. This is rate damping. Note that in this case, Fig. 503, the amount of drag (due to the current) is directly proportional to the speed at which the motor coasts. The faster it turns when the relay opens, the more drag, etc. We want to lump all the damping forces together, as we did the masses. Remember that friction is proportional to speed, too. The greater the speed the greater the friction.

Finally, let us consider the force which actually makes the motor run. This force is directly proportional to the current through armature windings and since this, in turn, is governed by the amplifier, we will consider that this force does come from the amplifier and assign the letter  $G$  to represent this.

The response of the servomechanism is governed by these three factors: Moment of inertia, damping and gain. We can arrive at some interesting facts about a servo system by analyzing its response to various values of these factors. For example, there is a relationship which will tell us what the natural, or resonant, frequency of the servo will be:

$$\text{Resonant frequency (cps)} = \frac{\sqrt{\frac{G}{I}}}{2\pi}$$

The inertia ( $I$ ) must be expressed in Slug  $\text{ft}^2 = \frac{32.2}{\text{Weight in lbs.}}$

The gain must be expressed in foot pounds of torque. Damping is expressed in foot pounds per radian. An example, using a commercially available servo motor, is worked out for you on page 100.

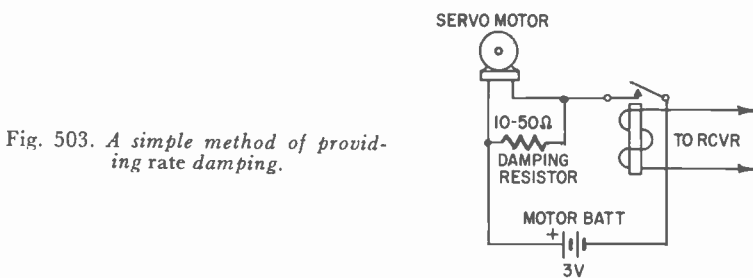


Fig. 503. *A simple method of providing rate damping.*

It is also possible to tell, by mathematical analysis whether the servo output shaft will position the fin quickly and accurately to a given position without hunting, whether it will oscillate, or whether it will position it very slowly.

Actually, what is done mathematically is to arrive at a balance between the three factors which will give the desired response quickly and accurately to position the control surface without oscillation, or with just one overshoot. In most cases, the response of a servomechanism is primarily governed by the gain of the amplifier. If a system tends to be unstable we must reduce the gain or increase the damping. The damping is increased if we need rapid response; we reduce the gain if the response is faster than is actually needed.

In large servomechanisms there is another method of rate damping. It operates on the premise that quickly changing signals will be ampli-

fied more than slowly changing ones. In practice, this is accomplished by means of a rate network (Fig. 504). It works like this: When the input signal is a rapidly changing one, it is equivalent to a high frequency and thus finds capacitor (C1) a short circuit. This feeds a large input signal to the amplifier and produces a higher torque in the motor and it moves quickly. By the same token, if the feedback signal is changing rapidly, it passes through the capacitor quickly and acts as a braking signal to cause the output shaft to position quickly and accurately with a minimum of oscillation.

There is still another characteristic of a servomechanism you should note. A servo acts somewhat like a low-pass electronic filter. For example, if we were to send it a signal for up elevator and then down elevator, both times calling for full elevator deflection, and sending these signals at the rate of one signal per second, the elevator would

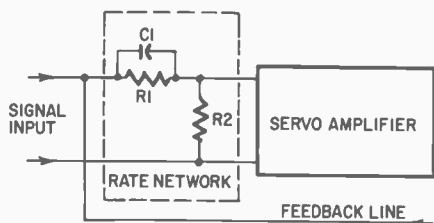


Fig. 504. A servomechanism with a rate network input has rate damping. As frequency of input increases, C1 becomes a short circuit. When very-low-frequency or dc signals are used, R1 allows this voltage to get to amplifier.

probably follow exactly as it should. If, however, we were to increase the rate at which we send these signals to, say, 50 per second, we might find that the elevator just doesn't deflect either way at all. The signals are changing so rapidly that the motor can't follow. The factor governing what this upper response limit will be is primarily the torque-to-inertia ratio of the motor. This means the armature should have very little mass (weight) and a very high torque capability. In fact, this torque-to-inertia ratio concept is used in evaluating how suitable a motor is for a servosystem.

As an example, suppose we get a signal from a potentiometer in place of a discriminator signal to a servo amplifier, as shown in Fig. 505. Here a second potentiometer is connected like the feedback potentiometer but with the voltages reversed. The shaft of this potentiometer is connected through a translating yoke to the output gear of a second motor. This motor has a variable resistance in series with its battery to control its speed.

When this second motor is turned on, and its output gear turns, it will move the potentiometer wiper arm back and forth at a rate determined by the motor speed. At a low speed we mark the extremes of the elevator deflection. Now we gradually increase the motor speed,

thus increasing the rate of the input signal variation. It is possible, if our servo is not too heavily damped, that we will be able to determine the servo resonant frequency. This will be that frequency (motor rotation speed) at which the elevator deflection is greater than at any other motor rotation speed with no increase in the voltage across the input potentiometer. The frequency will be directly equal to the number of motor revolutions per second (motor speed) since one revolution is equal to one cycle of input voltage.

We can also determine the bandpass. The upper limit is that frequency at which the elevator deflects only about three-fourths of its low frequency input value. The bandpass is that range of frequencies from zero to this amount.

Why would we be interested in these factors? First, if we are unable to determine any resonant rise our servo is heavily damped and we

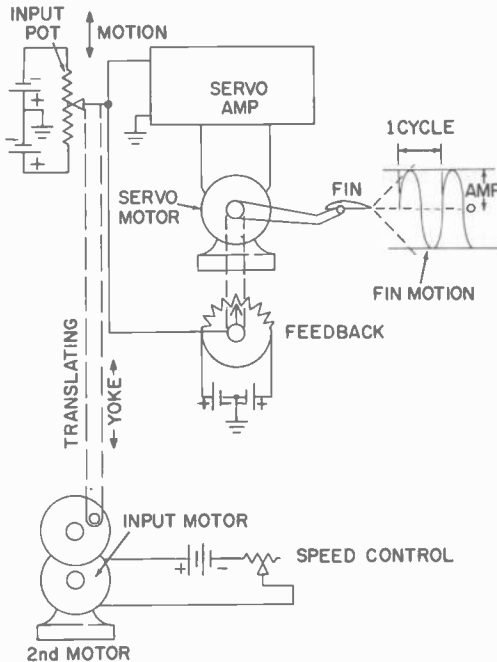


Fig. 505. Determining bandpass characteristics and linearity.

probably could utilize more amplifier gain. Second, we do not want to send control signals at a rate near the resonant frequency of the servo. This can cause the airplane to be overcontrolled or, in cases of little damping, can cause us to lose control. Third, if our bandpass is very low, we need more gain or a more rapidly responding motor.

## Design notes

Normally, when we build a proportional control servo system for a radio-controlled model, we select a suitable motor, add a feedback potentiometer and try to select an amplifier which will make it operate. It will be well to spend a few moments discussing some of the design concepts which would apply to this kind of servomechanism.

Start the whole process by selecting a servo motor. That shown in Fig. 506 has the necessary limit switches and feedback potentiometer built onto it by the manufacturer.

We are furnished some specifications with it:

Weight	.....	2 oz.
Power	.....	Excess of 32 in. oz. (through the gears)
Voltage	.....	3 volts
Current drain	.....	110 ma running, 325 ma stall
Feedback pot	.....	Resistance furnished as requested (2,000 ohms)

Consider the power rating first. This specification is torque and it is in inch ounces, 32 inch ounces of torque. Torque, remember, is force times distance, so if we put a one-inch lever on the motor shaft and hang a 32-ounce weight from the end the motor could move it. If we had a four-inch lever, we could lift eight ounces. Whatever the weight and the lever arm, the two, multiplied, must equal 32.

We want the servo to move a model airplane elevator. Some tests and calculations have shown that around 5 inch ounces of torque is adequate for control surfaces having up to 40 square inches of area. Therefore, a motor producing 32 inch ounces of torque is more than adequate.

With a servo motor selected, we must next determine the amplifier that will be needed to drive it. We will select transistors, of course, because of their small size and low voltage requirements. With a stall current for the motor of 325 ma it means that the starting current must be somewhere near this value and, even if it is only momentary, the transistors which drive the motor must pass this current easily. We shall refer to these as the motor controlling transistors. We will require one n-p-n type and one p-n-p type and both should have as nearly identical characteristics as possible because one will make the motor run in one direction while the other will make it reverse. A transistor manual indicates that the 2N143 and 2N144 will do nicely since they have the following characteristics:

$I_c$	$h_{fe}$ (alpha)	Collector volts
0.8 A	0.975	30

We do not need 0.8 ampere (800 ma). We could have selected a pair which had about a 500 ma  $I_c$  rating, but since these are a matched set, we chose them.

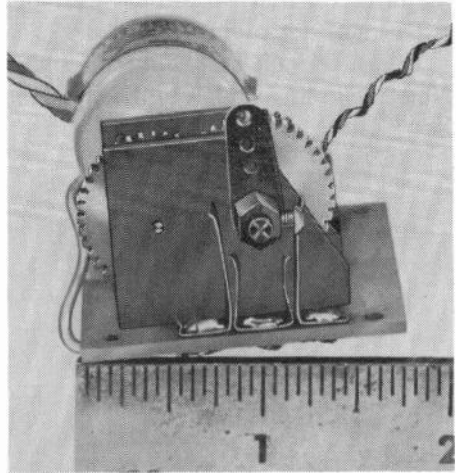


Fig. 506. Servo motor complete with limit switches and feedback potentiometer.

Next we need a set of characteristic curves for these transistors, such as those shown in Fig. 507. Since the load resistance will be small, we can assume that there will be little voltage drop to the collector until the current gets high. When the motor is running at full speed, it will drop the 3 volts across its terminals but we won't mind that for

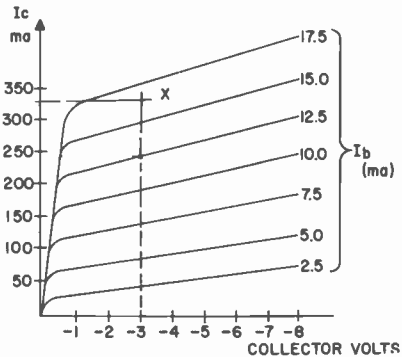


Fig. 507. Typical transistor characteristic curves.

it will then be running. What we want to determine, from the characteristic curves is the amount of base current we will need to produce the required motor-running current.

In Fig. 507 there is a dashed vertical line up to the 325 ma level and an X marked near the base current line required for this collector current. Actually, the vertical line might slope to the left which would

indicate that the collector voltage reduces as we draw more current, but for our purposes here we need not be concerned with that. The major fact is that we will need around 15 to 17 ma of base current for our motor controlling transistors.

A basic circuit for the motor-controlling section is given in Fig. 508. Note the limit switches in the collector circuits of each transistor. These

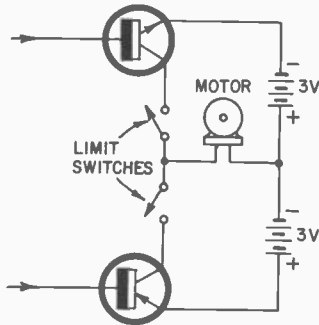


Fig. 508. Motor circuit with limit switches.

will automatically open the circuit when that particular transistor drives the motor lever arm to the desired limit.

We have two choices on the driver transistor input circuit configuration. We can direct couple them into the bases of the motor-controlling transistors (Fig. 509-a) or we can couple them through a resistor as shown in Fig. 509-b. There isn't too much difference in the operation.

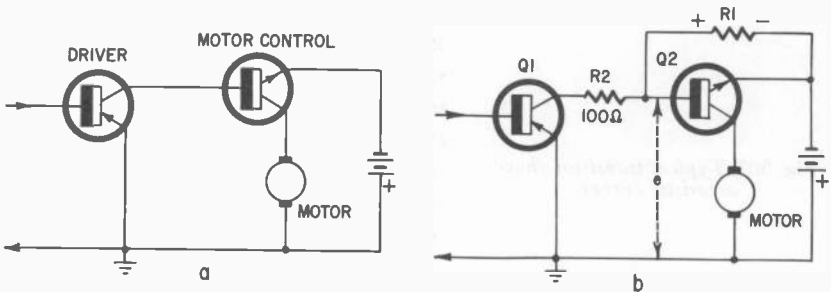


Fig. 509. Methods of connecting driver transistors. Half circuit is shown in each case.

For the driver we must select a transistor which will be able to pass at least 20 ma collector current when connected to the battery through a load consisting of the base-emitter resistance of the motor driver. We assume this total resistance to be in the order of 1,000 ohms.

In the circuit of Fig. 509-b, when Q1 conducts and current flows through R1, the polarity of the voltage drop across this resistance

would be as shown. This would apply a forward bias to the motor-controlling transistor and cause it to conduct. R2 is a small isolation resistor used to allow this positive potential to exist at the motor-controlling transistor base even though Q1 conducts to an extent which would make it a short circuit. R2 should be only about 100 ohms. The value of R1 then would have to be determined from the current through it, remembering of course, that it is in parallel with the base emitter resistance of the motor controlling transistor. Both in parallel should not produce a voltage drop between base and emitter larger than specified in the transistor manual.

Assume that we will use the circuit of Fig. 509-a. We would then look in a transistor manual for a pair of transistors, one n-p-n and one p-n-p, with collector ratings of at least 20 ma, for which we can draw a load line for 1,000-ohms. If the collector will be at 3 volts when the current is zero, this will establish one point on a curve such as Fig. 507. We can establish the other point by considering the collector voltage to be at zero when the full voltage drop appears across the load at 20 ma. Now, look at the curves again to see what base current will be required for the driver to produce the collector current swing.

A 2N187 and a 2N377 were selected for our p-n-p and n-p-n types respectively and each of these has a collector current rating of around 100 ma. We chose the base current bias so that only the required collector current of 20 ma actually flowed in the circuit.

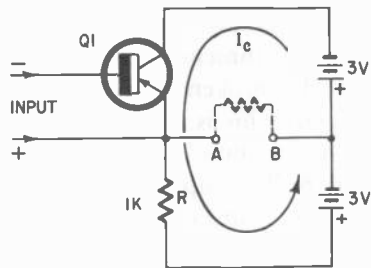


Fig. 510. *The input transistor circuit.*

An input transistor is needed which will supply the necessary base current to the motor-controlling transistors. Because of the complementary symmetry configuration of the driver circuit the input voltage must vary from positive to negative to produce the positive and negative base currents for each type.

The bridge configuration of the transistor circuit can be seen in Fig. 510. When the transistor collector-to-emitter resistance is equal to the 1,000-ohm fixed resistor R, there is no voltage difference between points A and B and thus no current flows through the dotted



resistance. The dotted resistance represents the base to emitter resistance of the complementary symmetry driver transistors.

When, due to an input-signal current which makes the transistor conduct more, the resistance between collector and emitter is less than the fixed resistance, point A will be at a higher negative potential than B and thus negative with respect to B. Current will flow from A to B.

When the current through the transistor decreases, its effective resistance is higher than that of the fixed resistance, A is less negative than B and current flows from B to A. A is positive with respect to B. Thus, through this bridge we have been able to get the bidirectional currents required to cause our transistor drivers to conduct and, in turn, the motor-controlling transistors and the motor itself.

Note that the input signal to the transistor of Fig. 510 need be only of one polarity. If we assume that it is operating class A, it only needs to conduct more or less to unbalance the bridge. It is also interesting to note the possibility of varying R with motor rotation to provide feedback, thus eliminating the requirement for extra feedback potentiometer batteries.

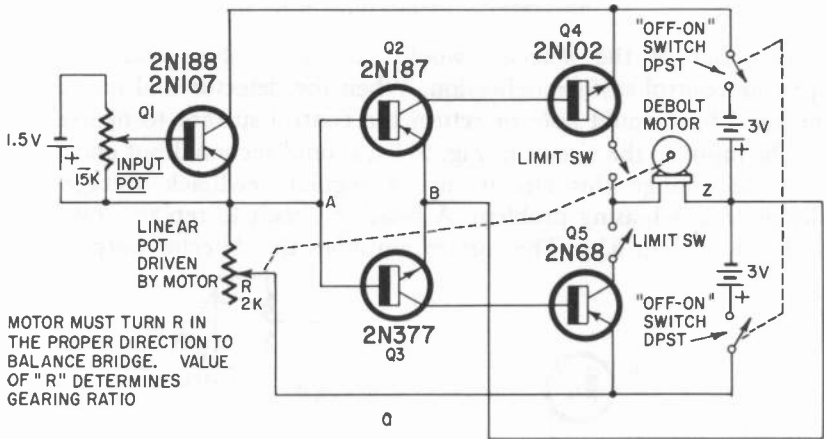
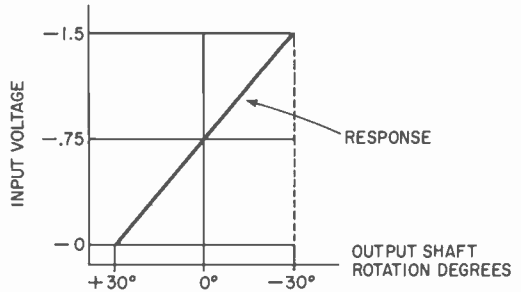
Based on the foregoing design, the circuit of Fig. 511-a was constructed and although the motor-controlling transistors differ (these happened to be on hand for the test) the operation was as expected. The servo operated smoothly and with a quick response. Positioning was accurate and easily controlled by varying the input potentiometer arm. The graph shows the response during the test.

It is recommended that when the circuit is constructed, the motor circuit be broken initially at Z in order to see if balance can be obtained. This is done by placing the leads of a voltmeter (we used the 6-volt scale of a 10,000-ohm-per-volt instrument) between points A and B. The input potentiometer was set at about half rotation (it should be a linear potentiometer of about 15,000 ohms). The servo motor potentiometer was adjusted by hand until there was no voltage differential between A and B. The motor circuit was then closed at Z and the input potentiometer varied.

If the feedback resistance value (R) is changed in the wrong direction by the motor, the motor drives immediately to one extreme deflection or the other and no intermediate positioning can be obtained. When the potentiometer is moved in the correct direction to balance the bridge, a small movement of the input potentiometer wiper arm will result in a small displacement of the motor lever arm. In the servo used, the feedback potentiometer had three leads — red, green and yellow. The wiper arm was connected to the red lead. All that

was necessary to correct the direction of the feedback potentiometer rotation (we had it incorrect the first time) was to change the connection to the emitter from green to yellow leads. We then had to

Fig. 511-a. Motor control circuit.



loosen the servo motor lever arm and reposition it in the center position when circuit balance was obtained with the input potentiometer set at center and the feedback potentiometer adjusted as mentioned previously for balance (zero voltage) between A and B. The feedback potentiometer should have at least a 2-watt rating.

For radio control applications this kind of servo system simplifies the detector problem. A simple *slope detector* might be used instead of a discriminator to provide a unidirectional negative voltage with a change in tone frequency. This would require, however, that a tone be transmitted all the time since zero voltage out of the detector would result in full control surface deflection.

It might be possible to provide a fixed bias for the input transistor as in Fig. 511-b. In this case, the minus output from a slope detector would add to the bias resulting in a greater negative voltage. This results in control surface deflection in one direction, while a positive

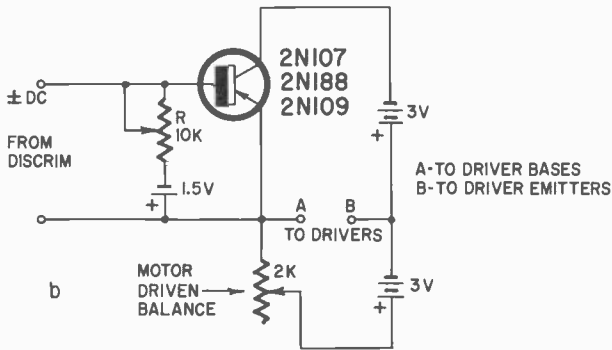


Fig. 511-b. Bias method to allow plus-minus input from discriminator. Adjust  $R$  for balance.

voltage out of the detector would cancel the bias and result in opposite control surface deflection. When the detector had no output, the fixed bias would hold or return the control surface to neutral.

The input to the circuit in Fig. 511-a is unidirectional but one might want to change this circuit, use a regular feedback voltage and eliminate this biasing problem. A possible circuit to replace this input is shown in Fig. 512. This circuit amplifies the detector output. The

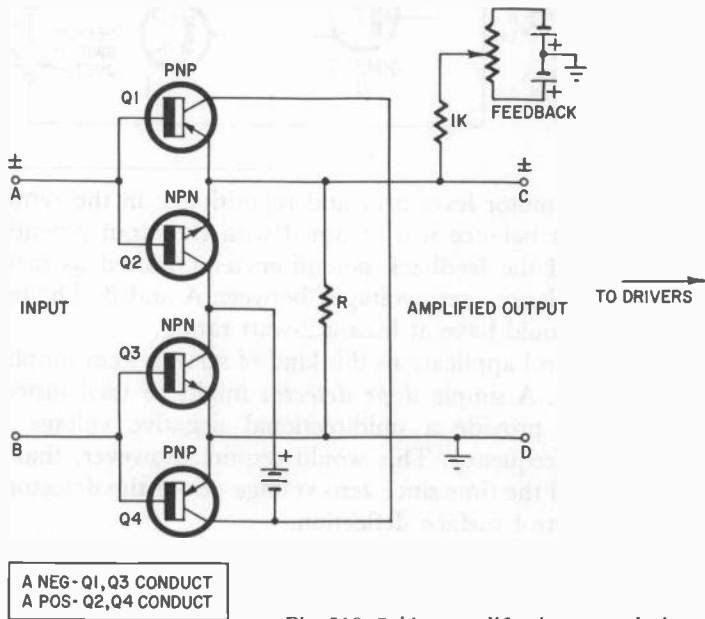


Fig. 512. Bridge amplifier for two polarity output. Do not connect B and D together through ground.

resistance  $R$  may or may not be necessary. Note that point  $B$  must not be connected to  $D$ , but  $D$  should be connected to the common ground wire of the servo amplifier.

In designing the servo amplifier, one may use many methods. Essentially, a current gain is desired which might serve as the basis for the number and types of stages used. For example, in the case considered, the motor requires 325 ma maximum. We could assume that the output of a detector is 50 microamperes (or less). If we use the 50 microampere figure, the current gain required is:

$$\frac{0.3}{50 \times 10^{-6}} = \frac{300 \times 10^3}{50} = 6,000$$

We had noted previously that the  $h_{fe}$  rating of the motor-controlling transistors was 0.975, and we remember that current gain is:

$$\beta = \frac{\alpha}{1-\alpha}$$

Solving this we get:

$$\frac{0.975}{1-0.975} = \frac{0.975}{0.025} = 39$$

With a current gain of 39 for the motor stage, this leaves:

$$\frac{6,000}{39} = 154$$

If we select a motor-controlling transistor with a gain of 15, then a first stage with a gain of 11 will be more than adequate. Any method of connecting these three transistors so that they will produce these individual stage gains and a bidirectional current output will accomplish the servoamplifier design purpose.

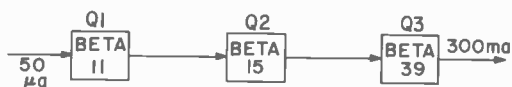


Fig. 513. Current gains specified in blocks.

Fig. 513 shows a block design of this concept. The overall gain is the product of the individual stage gains and totals more than 6,000.

### The linearity problem

Up to this time we have been concerned with the operation of the servomechanism. Now that we have a basic system, let us discuss refinements. The biggest improvement in performance will be to improve the linearity.

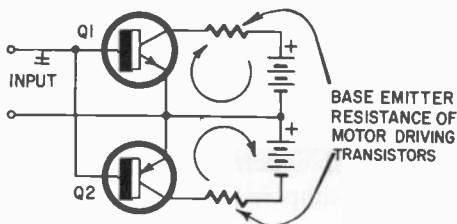
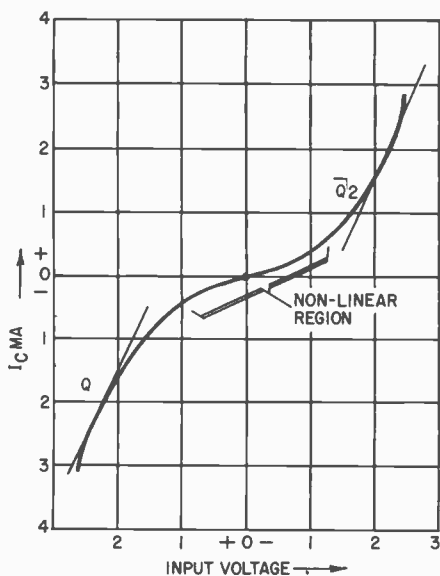


Fig. 514. Graph showing nonlinearity. Note linear portions reached when some collector current flows.

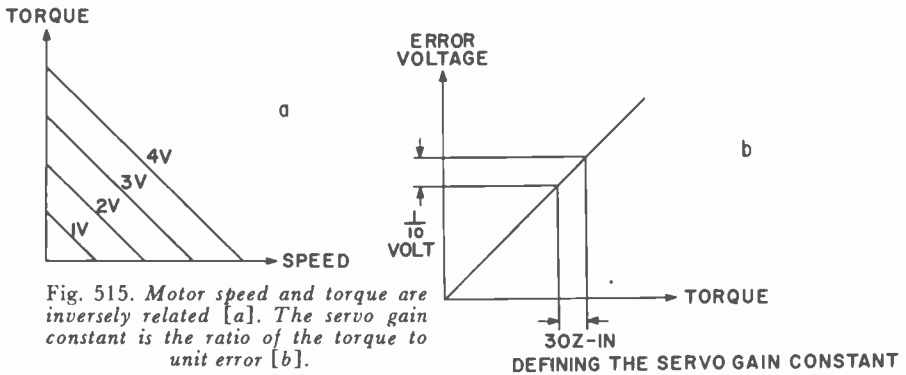
Fig. 514 shows a curve for a complementary circuit such as we used for the drivers. This same type of curve may apply also to the motor-controlling transistors. The important concept here is that, since we are using no bias on either transistor, they are theoretically operating on the lower portion of the characteristic curve. This introduces a nonlinearity just as it would in a vacuum-tube amplifier. For proper design of the servo amplifier, each stage of the transistor amplifier should be so biased that it operates on the linear part of the characteristic curve as much as possible.

### Estimating servo performance

While it is possible to analyze a servomechanism's performance mathematically, this is beyond the scope of this text. We will, however, try to show some basic calculations which can be made and how the answers arrived at may help one to estimate the performance of his servo. One of the most important concepts of the completed system is its resonant frequency and we stated a formula for this earlier:

$$\text{Resonant frequency (cps)} = \frac{\sqrt{\frac{G}{I}}}{2\pi}$$

In general, the higher the resonant frequency the better the servo performance will be. Now refer to Fig. 515-a which is a theoretical motor speed-torque-voltage curve for the servo motor. We see that



the speed and torque are inversely related and that both are proportional to the applied voltage. In Fig. 515-b we have shown a curve which one might obtain experimentally by fastening a spring gage to the servo motor output lever and then varying the input voltage to the servo amplifier. This is done to obtain a numerical value for  $G$  which is the servo gain constant:

$$G = \frac{\text{torque}}{\text{unit error}}$$

The error voltage would be the difference between the input and feedback voltage and that amount which causes the motor to turn.

The moment of inertia ( $I$ ) could be obtained from the manufacturer. For the little motor shown previously, an estimated value is  $10 \times 10^{-6}$  slug ft<sup>2</sup>. For purposes of calculation, we are going to estimate that the torque is linear and that through the amplifier we obtain 3 ounce-inches of torque for a 0.1 volt error. Our unit error then is 0.1 volt. (Note:  $G = 3$  ounce inches. To convert to foot pounds, we divide  $G$  by  $12 \times 16$ .)

$$\begin{aligned} \text{freq} &= \frac{\sqrt{\frac{3}{\frac{(12)(16)}{10 \times 10^{-6}}}}} {6.28} = \frac{\sqrt{\frac{0.0156}{10 \times 10^{-6}}}} {6.28} \\ &= \frac{\sqrt{\frac{15600}{10}}}{6.28} = \frac{\sqrt{1560}}{6.28} = \frac{39.5}{6.28} = 6.29 \text{ cps} \end{aligned}$$

This is not too high a frequency. Servomechanisms may have resonant frequencies from 20 to 50 cps depending on the type and application, but it is high enough for our purposes. This means that if the

servo started hunting, it would oscillate the output lever at this frequency.

The best servo motor is one which has a high torque-to-inertia ratio. Generally, this means it must have a long armature with a small diameter which would cause the diagonal of Fig. 515-b to be more vertical. We can use Fig. 515-a to estimate how much voltage will be required for a given speed and torque output. The speed determines how fast the servo will move and the torque, of course, will determine the control-surface load that can be moved.

### Relay servomechanisms

It would be well to spend a few moments discussing that type of servo amplifier which uses relays to energize the motor. In general,

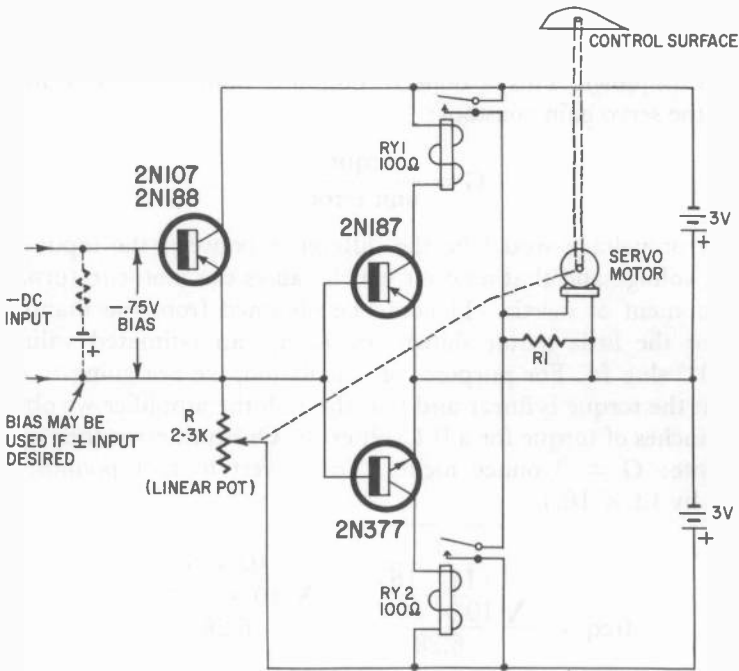


Fig. 516. Relay servo amplifier. Relays should operate on 3 volts, 20 to 30 ma.

the system is similar to those previously discussed except that each time the relay closes full power is applied to the motor and there is no gradual power variation as with the non-relay type. Such a circuit is shown in Fig. 516.

Note that when the dc input is  $-0.75$  volt, both relays are open. As the input level goes toward zero volts RY2 would close, and as the input increased to  $-1.5$  volts RY1 would close. As each relay closed, the motor would run until, in moving R, the circuit would again be balanced, causing the energized relay to open.

The problem with this kind of servo is the overshoot. Since full power is applied to the motor right up to the last moment as the circuit approaches balance, the motor will be more likely to coast past the desired position. When it does so, the input circuit is unbalanced in the opposite direction, due to excessive change in the setting or R, and the other relay closes and applies full reverse power.

If there is not enough damping the system will hunt. The motor will oscillate back and forth as R continually overshoots the balance position. It is possible to increase the damping by adding R1, a 10- to 50-ohm resistor across the motor terminals, as well as by adding friction to the motor shaft.

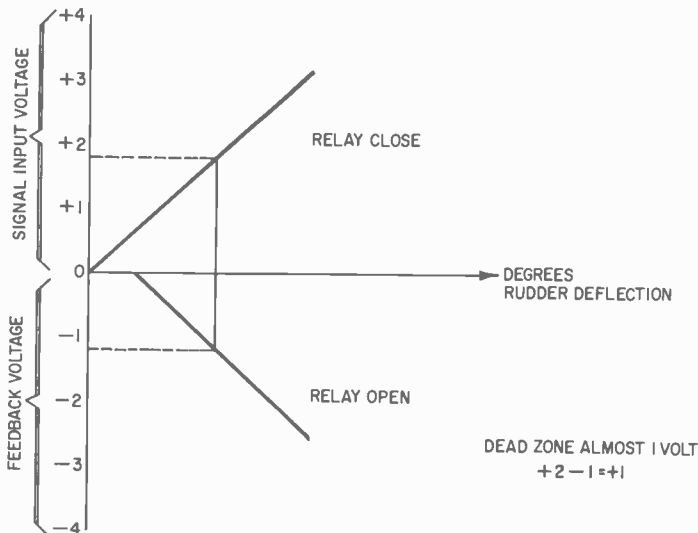


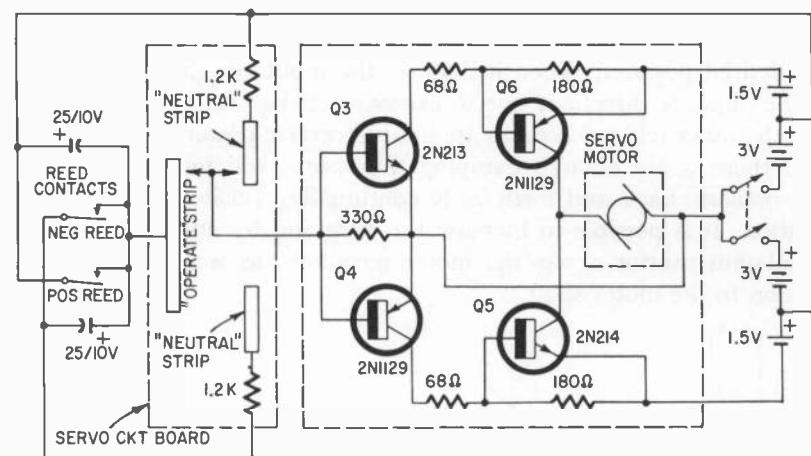
Fig. 517. Relay servo "dead zone".

Fig. 517 illustrates the effect of the relay dead zone on the accuracy of positioning. Since each relay has a definite pull-in and drop-out current value, the input voltage can change some amount before the motor is actually energized. The closer we make the pull-in drop-out current adjustments, the more likely the system is to oscillate due to overshooting the balancing point.

In the design of this kind of system, you will need to expend great effort to obtain a good tight damping system. In fact, you should incor-

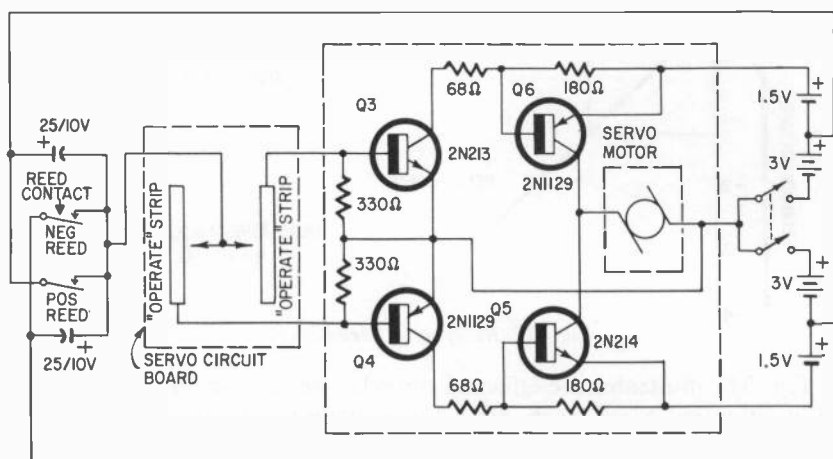


porate a magnetic brake in the motor-drive circuit so that when either relay is energized, the brake is released. When both relays are de-energized, the brake immediately locks the control system in place. This, together with a very minimum difference between pull-in and drop-out values of relay current would make this system very fast, accurate and practical.



NEUTRALIZING COMPUTER CIRCUIT

a



TRIMMABLE COMPUTER CIRCUIT

b

Fig. 518. Circuits adaptable to proportional control. Circuit above shows arrangement for a neutralizing servo circuit while lower circuit is the trim type servo.

## Some proportional control servo circuits

The circuits of Figs. 518-a and 518-b are for servo amplifiers in which the motor drives sliding limit-switch contacts to provide a neutralizing operation in (a) and a positioning operation in (b). These circuits are designed to operate with a standard reed decoder.

In Fig. 518-a when the negative reed closes its circuit  $-3$  volts (with respect to their emitters) is applied to the bases of  $Q_3$  and  $Q_4$ . This causes  $Q_4$  to conduct and it, in making  $Q_4$  conduct, sets the motor running. As the motor runs, the slider is moved off the operate strip and only makes contact with the upper neutral strip.

While the slider is in contact with both the operate and neutral strips, the operating voltage is developed across the  $1,200$ -ohm resistor which is between the  $-3$ -volt and  $+3$ -volt terminals.

When the reed is opened, the only input to  $Q_3$  and  $Q_4$  is the potential from the upper battery so the motor reverses and drives the slider to the no-contact center section which is neutral.

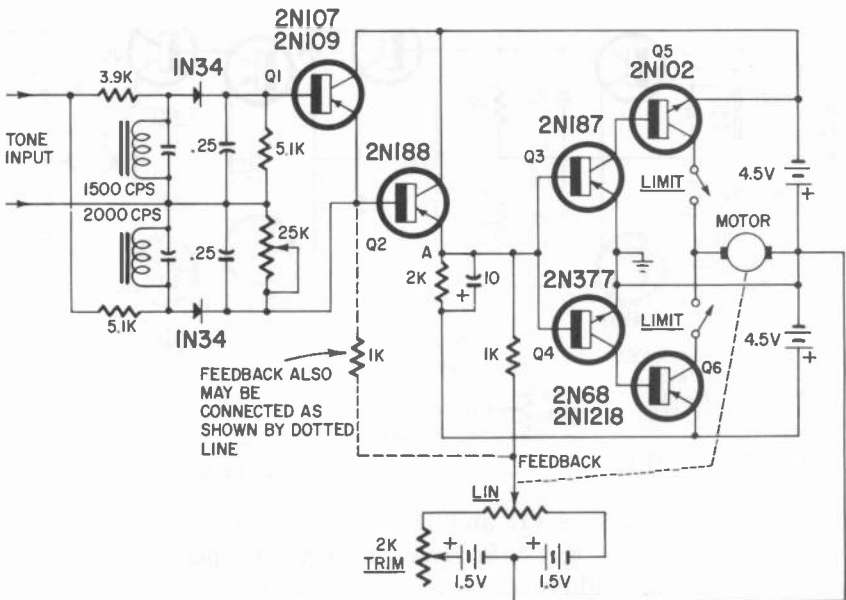


Fig. 519. *Experimental servo driven by a discriminator.*

In Fig. 518-b the neutral strips have been omitted, so the movement of the motor (and thus the control surface) is proportional to the

length of time the signal for either reed is on. To reverse the motor, the opposite reed must be energized.

This amplifier might be used in other applications with a different type input for Q3 and Q4.

Fig. 519 shows a servo amplifier connected to a discriminator of the type described earlier. The operation was quite satisfactory and the sensitivity adequate for most control purposes. The theory of operation is that the discriminator voltage applied to Q1 between base and emitter will govern the flow of current through this transistor. Since the current has to pass through the base and emitter of Q2 to complete the circuit to the positive terminal of the lower battery, it controls the current of Q2. A change of current through Q2 and its 2,000-ohm emitter resistor shifts the bridge balance so that either a positive or a negative voltage is presented to the bases of Q3 and Q4. The feedback potentiometer connected as shown will cancel the bridge unbalance electrically when it is driven in the proper direction.

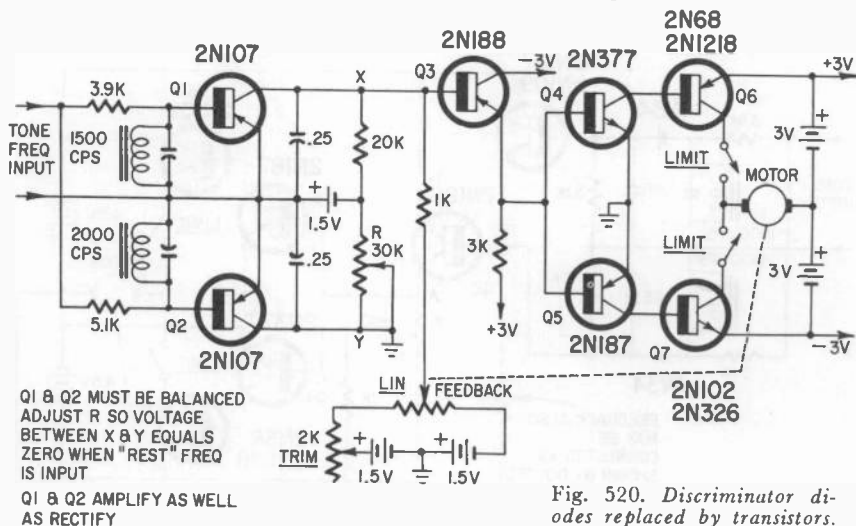


Fig. 520. Discriminator diodes replaced by transistors.

In Fig. 520 transistors Q1 and Q2 substitute for the 1N34 diodes used in the circuit of Fig. 519. Biased to a point where they rectify as well as amplify, additional system gain can be obtained. Circuit balance can be very difficult and carefully matched parts are needed for good linearity. Differences in the input signal (tone) level, transistor characteristics, tuned circuit Q and filter capacitor leakage must all be balanced for a perfect system. Each variation in balance reduces the abilities of the circuit and the low-tolerance parts required (1% or 5%) increases the cost considerably.

# fundamentals of rockets

## chapter 6

When we consider the future of radio control, we must not overlook the rocket as a controlled vehicle. With proper vocational guidance and personal effort, this could well provide the foundation of a career in this exciting field. To the old timer in the radio-control field, this could supply an added stimulus, a new challenge to his abilities and imagination. To anyone interested in the fields of science and space technology, it is hoped that this and the following chapter will provide greater understanding of space conquering vehicles.

We have to start by learning the basic concepts which will allow us to design and build some model rockets in the chapters to follow.

### **Radio control of rockets**

When considering controlled rockets, we must at once readjust our thinking concerning the object that the commands will be sent to. We must modify our thinking in terms of the speed at which these commands must be sent and executed. We must re-evaluate the methods used to keep track of the controlled rocket; that is, its position and its altitude.

A controlled model airplane is easy to watch with just our eyes. We can see if it is flying straight, turning, has one wing high or nosing up, and we can send commands manually to correct these problems. With a rocket the command problem is divided into two parts, both of which must be performed automatically because of the tremendous speeds involved.

Begin your examination of this new type of vehicle by looking at the

rocket body. Note in Fig. 601-a that it is symmetrical along its longitudinal (roll) axis and in Fig. 601-b that its fins are placed equidistant around the tail and that, in this example, it does not have wings. Note also that we have defined three axes about which this body can move, or rotate. These axes are the *pitch axis*, which is an imaginary horizontal line through the center of gravity of the rocket; the *yaw axis* is

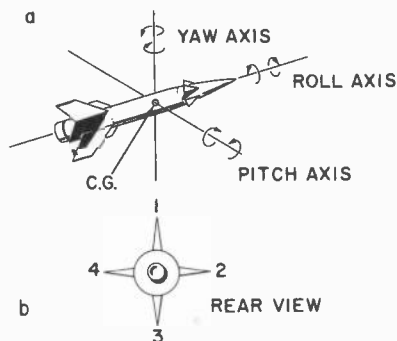


Fig. 601. Rocket axes and fin designation.

an imaginary vertical line through the center of gravity, and the *roll axis* is the longitudinal axis of the rocket.

Here is the first problem in a rocket. A rocket without automatic controls will spin during the first part of its flight because of unequal blast-off pressures and other conditions. It points in the direction it is going because of its fins. However, the operator has no way of telling which fins are in the rudder position and which fins are in the elevator position.

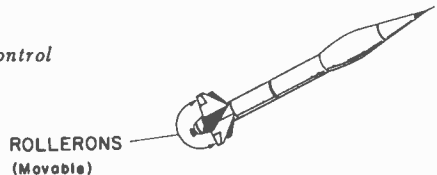
How important is this? If we were to designate fins 1 and 3 (Fig. 601-b), say, as rudders, and we planned to send signals to these to make the rocket turn, we might find ourselves sending a signal for left and having the rocket going up. Thus you see that if this symmetrical rocket rolls, we won't know what our command will produce. What is required is a roll-control system built right into the rocket to keep it from rolling, to hold the rudders (1 and 3) in the required vertical position and the elevators (2 and 4) in their proper horizontal position. Then we can send commands and make the rocket go where we wish.

To control the spin (or roll) of a rocket, it is necessary to provide two small control surfaces (Fig. 602) which can be moved differentially, like airplane ailerons, to counteract the roll. In some rockets the regular steering fins are used; in others the rocket jet may be directed to prevent roll, or small auxiliary jets may be provided on the rocket

body for this purpose. Whatever method is used, these surfaces (or jets) must be moved by some mechanism, and this mechanism is called the roll-control servomechanism.

For this roll-control servomechanism to move the roll-control surfaces in the correct direction, it must be able to tell when the rocket is rolling. Sound funny? Have you ever been up in a plane, or seen

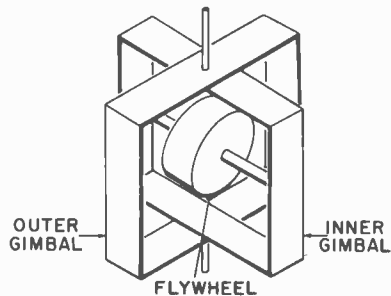
Fig. 602. *Roll is controlled by roll-control surfaces.*



pictures from an airplane which show the earth turning? If you were out in space without any nearby object, could you tell whether you were turning or whether the stars and planets were turning instead? We must provide our servomechanism with some means by which it can tell whether the rocket is rolling or not. We can do this with a gyroscope.

Perhaps you have had experience with the gyroscope as a toy. Like a top, it stands upright as long as it is spinning. A hoop or an auto-

Fig. 603. *Gyroscope is a flywheel in a gimbal system.*



mobile tire will remain erect as long as it is rolling. If you ever had a toy gyroscope you may remember seeing it remain erect as it slid down a string or balanced in your hand. What is peculiar about the gyroscope? Think of this: as long as your gyroscope is spinning it tries to keep its spin axis pointed, say vertical. You can move it around on the palm of your hand but it doesn't tip or fall over — it keeps its axis pointing up.

This phenomenon is known as rigidity in space and is a property possessed by every spinning mass. If we take this gyroscope or flywheel, mount it in a series of rings called gimbals, spin it at a high speed, place

it in a missile, it will keep its axis always pointed in the same direction. This will provide the rocket with a reference so that it can tell when it is rolling, in which direction, and how much. Fig. 603 shows the basic flywheel mounted in its gimbal system. Fig. 604 shows the complicated roll and steering control mechanism of the Nike Hercules (Army).

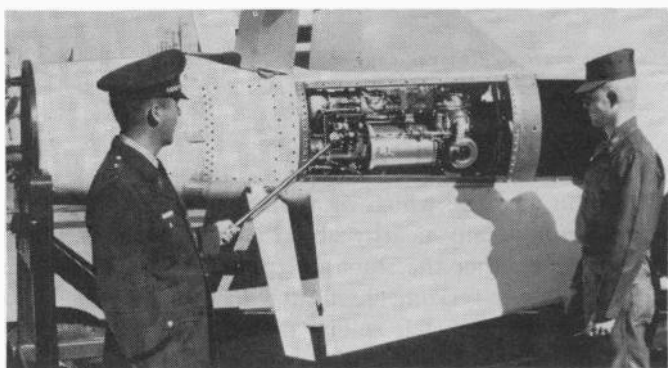


Fig. 604. Roll and steering-control mechanism of Nike Hercules.

The gyroscope can detect the direction and amount of roll and produce a signal which will cause the servomechanism to deflect the roll control surfaces in the proper direction and in the proper amount. Fig. 605 shows the basic gimballed flywheel mounted in a rocket

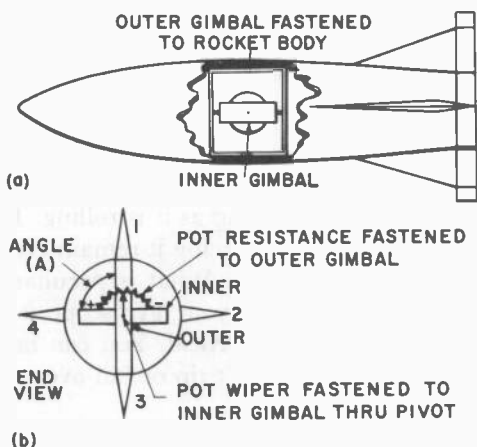
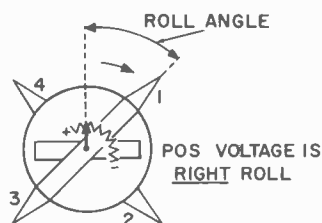
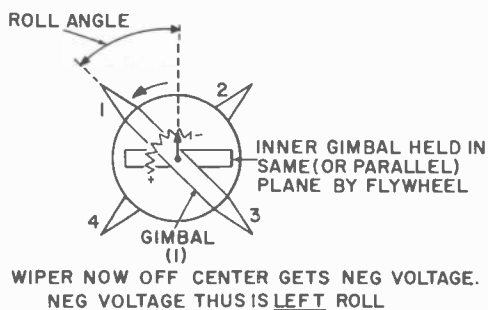


Fig. 605. Gyro mounting in rocket to detect roll.

missile with the flywheel axis perpendicular to the longitudinal axis of the missile. Fig. 606 shows another view of this same gyroscope. Note that we have added a potentiometer to the gimbal system. The wiper arm of the potentiometer is fastened to the inner gimbal; the resistance portion of the potentiometer is fastened to the outer gimbal. When angle A (see Fig. 605-b) is  $90^\circ$  the wiper is centered on the resistance. If we move the inner gimbal counterclockwise while the outer gimbal is held in its vertical position by the rocket body the wiper arm will



AMOUNT OF VOLTAGE PROPORTIONAL TO ROLL ANGLE  
POLARITY OF VOLTAGE STATES DIRECTION OF ROLL

Fig. 606. Potentiometer voltage indicates direction of roll.

move toward the positive end of the potentiometer resistance. If we turn the inner gimbal clockwise, increasing angle A, the wiper arm will move toward the negative end of the resistance.

When operating in the rocket guidance system, the action is a little different since the inner gimbal is held in a fixed position by the gyroscope while the outer gimbal, fixed to the rocket body, is the one that actually rotates. Thus when the *body* of the rocket rolls counter-



clockwise, the resistance moves, bringing its negative end toward the wiper. If the rocket should roll clockwise, the resistance moves to bring its positive end toward the wiper. When the wiper is at the center of the resistance, it has zero potential. The amount of roll can be measured by how high the voltage is while the polarity of that voltage will indicate the direction of the roll. A servo system can use this voltage to deflect the fins in a method similar to those in Chapter 5.

Rocket servos may be electric, pneumatic or electrohydraulic, types powerful enough to move control surfaces against torques as high as 50,000 inch-pounds.

In guidance servo systems the input signal must indicate the amount, direction and rate of roll. The rate is how fast the body is turning. The block diagram of Fig. 607 shows how a simple RC

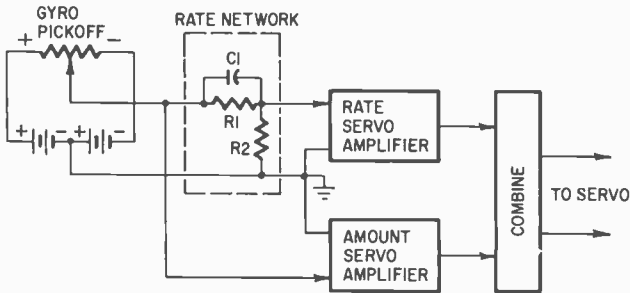


Fig. 607. Simplified diagram of rocket roll-control system. Rate and amount are combined in proper proportion to prevent roll.

(resistance-capacitance) network can produce a rate signal from the same signal that indicates the amount of roll. These two signals are amplified separately, then combined to control the correcting servo.

## Aerodynamics of the rocket

The control problem of guiding a rocket is largely connected with the aerodynamic problem, much as it is in the case of the model airplane. In the rocket, however, we are concerned with much higher speeds, and since the motion is near the speed of sound (about 700 miles per hour), we must also consider such things as the shock waves which can affect the control problem. The shock waves are just one effect; there is another. Because the rocket moves so fast, slight variations (nonsymmetry) in the body construction can cause lift and drag forces that are ignored at lower speeds.

The concept of a shock wave is not too difficult. Just imagine that

the atmosphere is filled with little molecules of air. When traveling at subsonic speeds a pressure wave or disturbance is set up in the air, like a sound wave. This wave travels ahead of the moving body, warning the molecules of air that the body is coming. The pressure disturbance thus precedes the rocket body.

As speed increases, the body catches up with these pressure disturbances. In fact, when the body is moving at the speed of sound it is moving with the same speed as that of the pressure disturbance. There can be no warning that the body is coming and the pressure waves tend to build up and remain, like a barrier, at the tip of the rocket.

The wave that is formed is called a shock or *mach wave*. (The mach number is the ratio: speed of body/speed of sound.) Since the speed of sound is about 700 miles per hour (it varies with temperature and barometric pressure), a rocket would be going at mach 1 when it is going 700 miles per hour, mach 2 at 1,400 mph.

Two kinds of pressure waves are set up around any projection when it is traveling at, or faster than, the speed of sound. These are the normal shock wave and the oblique shock wave as illustrated in Figs. 608-b and -c. There will be an oblique shock wave when the body is moving faster than the speed of sound, and the mach angle of Fig. 608 is indicative of how much faster than that of sound the rocket speed is. The smaller the angle, the greater the speed, etc.

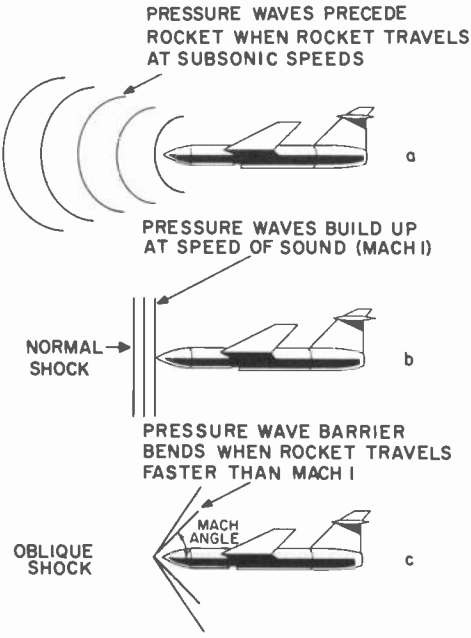


Fig. 608. Concept of a shock wave.

The effect this has on the control problem is that such shock waves will form at the tips of the fins and body. Since they are generally V shaped, they can encompass part of the fin in the shock wave region while leaving the rest outside, as shown in Fig. 609-a. The control

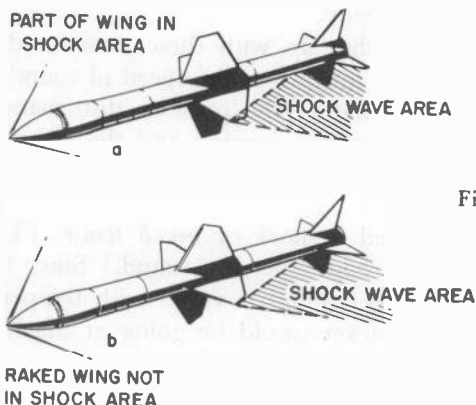


Fig. 609. Effect of shock waves on control.

forces will be different for the two different regions, and thus we could have instability, and a rocket we could not control.

We desire a fin that is entirely out of the shock-wave region when the rocket is moving at the design speed (Fig. 609-b). This accounts for the many different shapes of fins, which are designed from calculations and experiments to insure that the fins remain outside the shock-wave region.

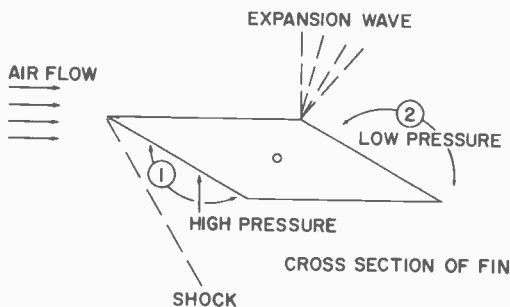


Fig. 610. Shock and expansion waves on fin. Lift is due to high pressure at 1 and low-pressure region, 2.

The cross-sectional area of a rocket fin differs from that of an airplane. It may be symmetrical and rounded on each side, or it may be diamond-shaped, as shown in Fig. 610. There is also a different concept of lift with the rocket fin. After the airflow passes through

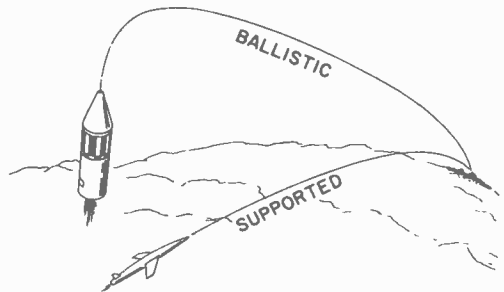
the shock wave, its pressure increases, while its velocity decreases. When the air passes through an expansion wave, its velocity increases and its pressure decreases. Thus, as shown in Fig. 610, there are two primary lift regions on this type of airfoil, sides 1 and 2.

Finally, at the speeds at which the rocket travels, the body itself contributes considerable lift which makes it possible to have just tail surfaces for control and stability. In some rockets jets are used to control direction (even the rear fins are omitted) and keep the rocket following a stable trajectory.

### Guidance systems

There are eight basic guidance systems which have use in the guided missile field today. Five of these are normally associated with surface-to-surface missiles (SSM). Here the missile follows a fixed-type trajectory from the launching point to the target. These trajectories may be ballistic or supported, as shown in Fig. 611. In either

Fig. 611. Surface-to-surface missile [SSM] trajectories.



case, the path of the missile to the target is set before it is launched. Then, after takeoff, the position of the missile is adjusted to coincide with this path. Note that for a ballistic trajectory the missile is launched vertically, pitches over towards the target at some fixed angle, continues to climb until the propellants are shut off or used up, and then follows a free-flight (unpowered) path to the target. Some ballistic missiles reach a height of 25 to 50 miles, and travel at speeds greater than 3,700 miles per hour. The missile flying a supported trajectory may be launched at any angle from horizontal. It climbs to its operating altitude, then flies at a relatively constant altitude, and dives or glides to impact at the target.

### Preset guide

In a preset system, guidance signals are generated in a timed sequence in a device known as a programmer which is mounted in the missile body. This time sequence is set before the missile is launched and cannot be changed once the missile has taken off.

This system is a simple and reliable form of guidance and is used in many missiles today. As the missile is launched, the programmer heads the missile in the general direction of the target and prepares the missile for the midcourse phase of flight. A preset guidance system may also be used when it is desired to test a propulsion system or airframe. In this way, important data on performance may be obtained without the expense of a complicated control system.

A common example of a programmer is that used for an automatic washing machine. It controls the washing of clothes in a predetermined time sequence. The turning of the dial starts a clockwork mechanism that opens and closes contacts within the device in a predetermined manner. This action controls the washing cycle.

### **Terrestrial reference (earth reference)**

This is a reference system of guidance which uses devices in the missile to detect any change from a course or trajectory.

This type of guidance uses one or more of the properties of the earth and its surrounding medium to compare with preset data to indicate its position along the prescribed path. Some of these phenomena are: atmosphere, magnetic field, electric field, gravitational field and topography. A magnetic compass in the system gives a compass bearing to provide a lateral path control to the target. A small spinning propeller, for example, in the nose of the missile can be calibrated in revolutions per mile and could be a method of range control. An altimeter can be made to indicate when a particular altitude has been reached by the change in atmospheric pressure. The normal variations in each of these indicating elements makes such a system quite inaccurate when used over long distances.

As the basis for a guidance system much work will have to be done before the gravitational field of the earth can be used for missile guidance. The topography of the earth provides a more likely means of guidance. A television camera in the missile might be used to transmit information to a control station or to provide a picture for on-missile comparison to a predetermined course.

### **Radio navigation**

Radio navigation as a means of guidance control uses the arrival time of radio signals to determine a position.

The system is similar to the principle used in *loran*. Radio waves travel at the speed of light. Since this speed is known and the length of time required to send radio signals from one point to another can therefore be measured, the distance between the two points can also be determined. Fig. 612 illustrates two possible courses a missile

might follow, using radio navigation for guidance. The missile in Fig. 612-a flies a straight line path by comparing the time of arrival of pulses that are transmitted simultaneously by radio stations at R1 and R2. If the pulses arrive at the same time, the distance (range) from the missile to R1 will be equal to that from the missile to R2 and the missile will fly along a straight line. In Fig. 612-b the missile transmits

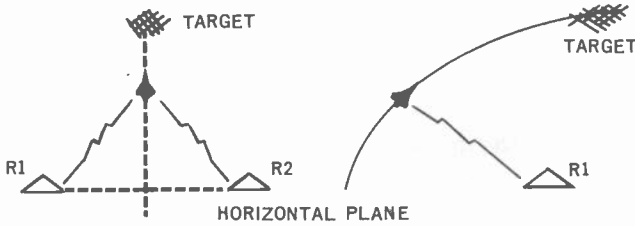


Fig. 612. Radio navigation paths.

pulses to a radio station at R1. As soon as a pulse arrives at R1, it is immediately transmitted back to the missile. The equipment measures the time it takes a pulse to travel to R1 and return, and thus measures its distance from R1. The missile then flies a course that keeps this time-interval constant and hence the distance from R1 is kept constant. The path will be an arc.

Although radio navigation can indicate circular or straight line courses, it is better to use a hyperbolic path. When a hyperbolic path is followed there will always be a fixed distance farther from one guidance station than from the other. Fig. 613 shows a grid of hyper-

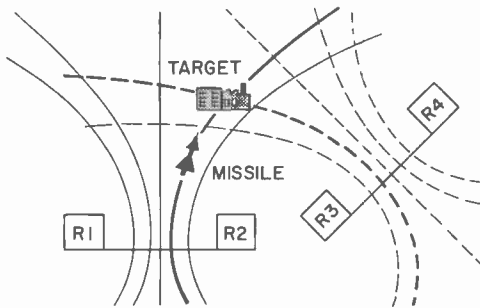


Fig. 613. Hyperbolic radio navigation.

bolae. The group of hyperbolas indicated by the solid lines is formed by radio stations R1 and R2, and those indicated by the dashed lines by radio stations R3 and R4. A missile flying along the heavy solid-

line hyperbola that passes over the target may always be located 1 mile farther from R1 than from R2. The control system computer causes the missile to fly along a hyperbolic path (heavy solid line) by comparing the arrival time of pulses transmitted simultaneously by R1 and R2. Similar equipment uses the pulses being transmitted by R3 and R4 which form another hyperbola (heavy dashed line) that passes through the target. When the relationships between the pulse arrival times indicate that the missile is crossing the heavy dashed line, and hence is over the target, signals are sent to the control surfaces which cause it to pitch over to crash (impact) into the target.

### **Automatic celestial navigation**

Automatic celestial navigation is a guidance system in which navigation is accomplished by making continuous celestial observations.

Such a navigation system aboard a guided missile is similar to that used for marine and aerial navigation. The navigator first positions the telescope of his sextant to establish a line of sight to certain known stars. He then measures the angles of elevation, from a horizontal reference, to these stars. The navigator at sea uses the horizon for his reference; the aerial navigator uses level-indicating bubbles on the sextant to provide an artificial horizon. By using the angles of elevation to two or more stars, the time the observations were made, and information from navigational tables, the navigator can compute his position.

In automatic celestial navigation the same procedure is followed. Star-tracking telescopes establish a line of sight to known stars. The system must be able to track stars in the daytime as well as at night; otherwise, daytime operation would be impossible. In the missile a stabilized platform provides the horizontal reference required. The computer takes the place of the navigator's brain and the navigation tables. It uses the angles of elevation to the known stars and the time the observations were made to compute the missile position. Knowing the coordinates of the target, the computer continuously sets a course to the target.

### **Inertial guidance**

Inertial guidance is a system that employs accelerometers to measure displacements. It can be used for all phases of guidance in either supported or ballistic missiles. The accelerometer measures the rate of change of velocity. It may be an increase or decrease in velocity. All movements of the missile result from the application of a force which accelerates the missile. A simple example will illustrate how these measured accelerations may be used for inertial guidance. If the

motor of a particular missile provides thrust which accelerates the missile constantly at 100 feet per second, what distance (displacement) will be covered with this acceleration for a period of 10 seconds? Assuming that the missile started from rest, at the end of 10 seconds, it would have a final velocity,  $V_f$ , as follows:

$$V_f = 100 \text{ ft/sec/sec} \times 10 \text{ seconds} = 1,000 \text{ ft/sec.}$$

Since the missile started from rest the average velocity ( $V_{av}$ ) is:

$$V_{av} = \frac{0 + 1,000}{2} = 500 \text{ ft/sec.}$$

The distance traveled during the 10 seconds (the displacement) is found by multiplying the average velocity by the time:

$$S = 500 \text{ ft/sec} \times 10 \text{ seconds} = 5,000 \text{ ft.}$$

Thus, distance traveled, or missile displacement, may be found by knowing the acceleration and the length of time it occurs. Actually, acceleration will not be constant. But the distance may still be found by the mathematical operation known as integration. Devices to

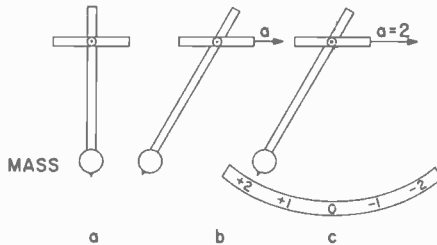


Fig. 614. Accelerometer principle.

perform integration are incorporated in the on-board missile computer. Accelerations are measured by accelerometers, the principle of which is best illustrated by a pendulum. Fig. 614-a shows a pendulum supported by a pivot through a crosspiece. If the crosspiece is accelerated to the right, as shown in Fig. 614-b, the pendulum will swing to the left by inertial reaction.

This same effect of inertia is experienced in a car when the driver steps on the gas. As the speed of the car increases you are pressed back against the seat.

Decreasing speed produces an opposite effect. When the brakes are applied you tend to fall forward. In an accelerometer, the direction of



reaction indicates acceleration or deceleration (Fig. 614-c), and the amount of reaction gives the value. The accelerometers are allowed to swing in only one plane, thus measuring changes of velocity in only one plane—two directions, one opposite the other. During flight the course is controlled to keep the lateral deviation from the correct path equal to zero. This keeps the missile on course. Fig. 615 shows two of

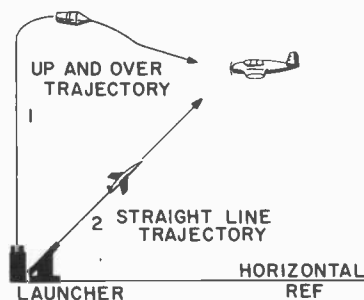


Fig. 615. Surface-to-air trajectories.

the many trajectories that may be used by the surface-to-air missile. Path 1 is an up-and-over type trajectory. On this path the missile quickly climbs out of the more dense lower atmosphere, and flies the greater portion of its course to the target in the less dense, higher atmosphere while the straight line type trajectory is just the reverse. A missile following this path to the target spends the major part of its flight in the dense, lower atmosphere, and during the terminal phase must climb steeply to intercept the target. Path 1 is a more efficient trajectory. The straight line trajectory is almost impossible to achieve except at close range.

### Command guidance

A command guidance system is much like that used to control planes. In this system the missile, too, is steered by commands sent to it by radio from a control station.

The control station keeps track of the relative positions of the target and the missile by using two radarlike systems, one of which tracks the missile while the other tracks the target. A computer takes this information and generates the command signals to be sent to the missile. In a typical command system, as shown in Fig. 616, the missile tracker and the target tracker feed missile and target position data to the computer, which in turn generates commands that are transmitted to the missile over the missile-tracking radar beam. The missile can thus be directed to fly on almost any trajectory to the intercept point.

## Beam rider control

In a beam rider guidance system (Fig. 617) the missile steers itself along the axis of a guidance beam.

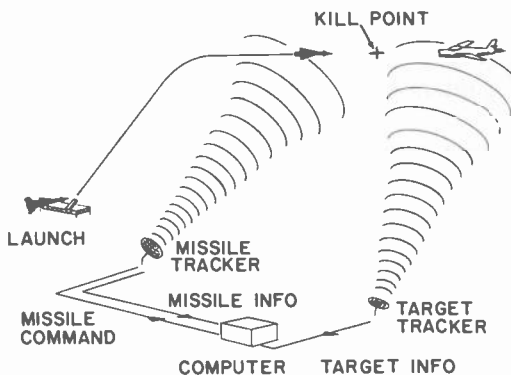


Fig. 616. *Command guidance operation.*

While any beam of energy, such as visible light or infrared, might be used, the more practical system uses a radar beam. In the simple case of the single-beam rider, the radar beam tracks a target in the air. The missile is launched into the beam where a receiver and computer in the missile maintain the position in the beam as it climbs to intercept the target.

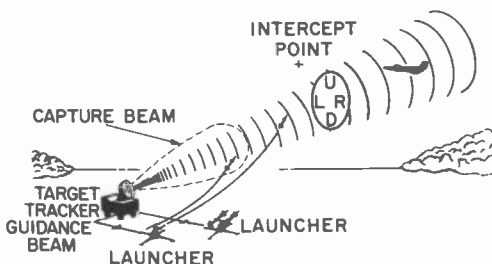


Fig. 617. *Single-beam rider. Missile steers itself in radar beam.*

## Homing guidance

Homing guidance is a system wherein a missile finds a target and steers itself toward it.

A homing guidance system consists of a target seeker in the missile, receptive to energy which is being radiated or reflected from the

target, and a computer which gets data from the target seeker and sends appropriate commands to the missile control surfaces, which keep the missile headed toward the target.

Characteristics of the target which may be used by the seeker for homing include: radar reflectivity; light, radio and sound emissions; infrared (heat) emissions; and magnetic and capacitive features. Homing guidance may be classified as active, semiactive or passive.

An active homing system (Fig. 618-a) is one in which all of the guidance equipment is contained aboard the missile. This includes a transmitter that illuminates the target, a seeker to receive reflected energy from the target and a computer. Once the active homing missile is launched, it acts independently of any outside agency and follows a correct path to the target.

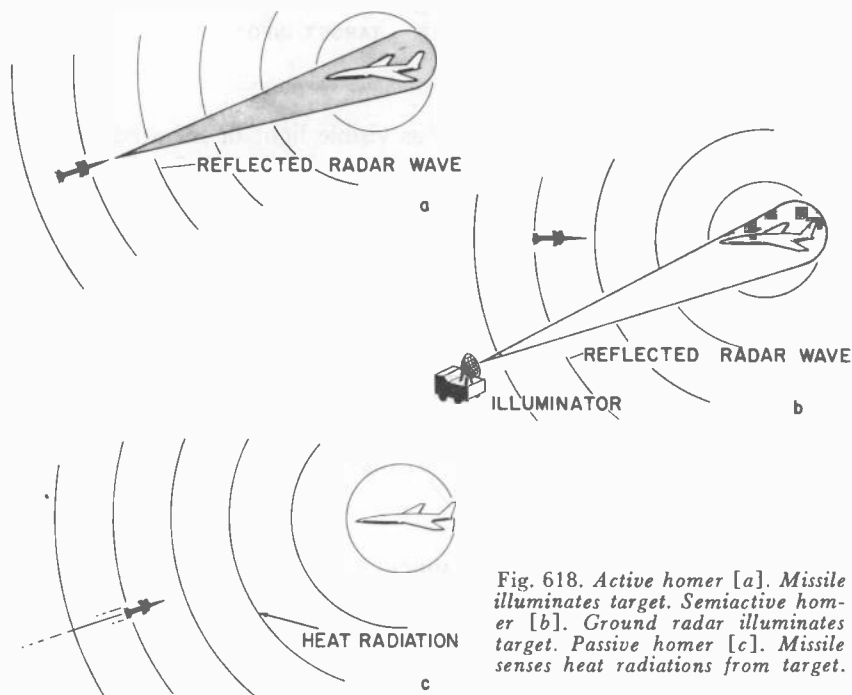


Fig. 618. Active homer [a]. Missile illuminates target. Semiactive homer [b]. Ground radar illuminates target. Passive homer [c]. Missile senses heat radiations from target.

In the semiactive homing system (Fig. 618-b) only the target-seeker receiver and a computer are contained aboard the missile. The target is illuminated by some outside source, usually an airborne or ground radar. After the missile is launched the target must be continuously illuminated until intercept.

A passive homing system (Fig. 618-c) makes use of the natural emanations from the target, such as infrared rays from engine heat or radio emissions. Since the target illuminates itself, the passive homing system acts independently of any outside agency in following its course to intercept.

## Telemetry

Telemetry means sending information from afar. In the telemetry system, however, we place the transmitter in the remote or moving location. Instead of sending commands back, it sends signals to the receiver from measuring instruments, which we can use immediately or record for future analysis.

One of the simplest telemetry systems is probably the Doppler system (so named because of the principle involved) which will give information on speed and position in space.

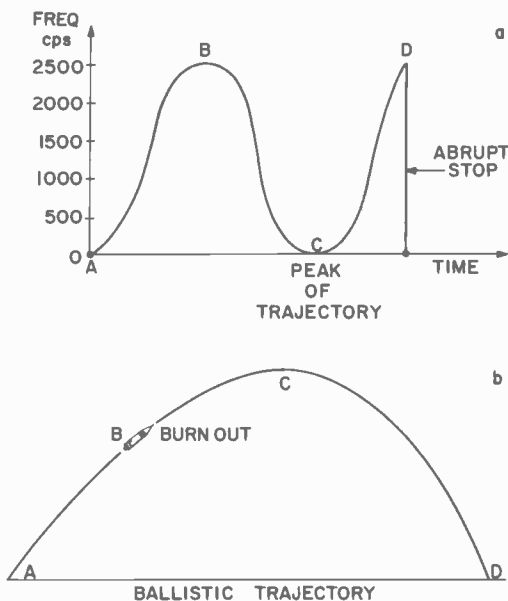


Fig. 619. The radial velocity of the rocket can be calculated by dividing the beat frequency by the frequency of the transmitter [a]. Ballistic trajectory is shown in drawing b.

A small crystal-controlled transmitter will send out a pure carrier. We can pick this up on a receiver and at the same time we can feed in a signal from a signal generator, which is tuned to exactly the same frequency as that of the transmitter until the two signals are exactly at zero beat.

When we put this transmitter in a rocket and launch it, there is an effect (the Doppler effect) which is the same as that noticed while listening to the horn of an approaching car or train. As it speeds toward you, the pitch of the moving sound generator is higher than when it is not moving. As the sound generator passes the pitch lowers. The same is true of the transmitter in the rocket or missile. As the rocket speeds away, increasing its distance from the launching site, the frequency of the signal sent out by its transmitter will arrive at the receiver lowered by an amount proportional to the speed of the rocket. This will produce a beat note which will be plainly audible to the human ear if the signal generator is kept tuned exactly to the frequency of the transmitter before the rocket was launched.

As the rocket is launched the speed of the moving transmitter will cause a frequency difference at the receiver which will be indicated by an increasing tone pitch. The sound we hear starts at a very low note, increases to some higher tone as the acceleration continues, decreases to zero again, and then begins increasing up to some high pitch where it will abruptly stop when it crashes into the ground. A graph of this effect is shown in Fig. 619, where the changing pitch is shown in relation to the trajectory. As the rocket speed increases and reaches a maximum, the pitch increases. The motor burns out at B, which is the highest pitch. The rocket then coasts on up to its peak altitude, decreasing in speed as it does so. As its speed decreases, the pitch also decreases. At the peak, the rocket is neither moving away nor returning to us, so the pitch is zero. When the rocket, under the pull of gravity, begins its descent, its speed again increases, and again we hear the tone increasing in pitch. The maximum velocity of the rocket is reached just as it hits the earth. Therefore, we hear at that moment the highest pitch and then silence. By listening to the tone of the receiver output, we can tell when the rocket has reached its peak, and if we clock the time it takes to reach the peak we can determine roughly its altitude, since the distance it will fall is:

$$S = \frac{1}{2}gt^2$$

(Where  $g$  is the gravitational constant, 32.2 feet per second, and  $t$  is the time the rocket is falling.) A very close approximation is that it will fall for as long as it took to reach peak altitude. Note that this situation will be true only for the high angle overhead shot. In ballistic trajectories the pitch will not decrease completely to zero at peak altitude since the rocket is still moving away from the ground receiver.

It is possible to determine the rocket speed from this tone information, knowing the frequency of the radio carrier. The tone we receive, in cycles per second, is exactly equal to the number of wavelengths

per second that the rocket is moving away from the receiver on a radial path. Let us use, for example, 144 mc, which has a wavelength of about 6.86 ft. At ten seconds after launching, if the tone is 1,000 cycles per second, the rocket speed is 6,860 ft. per second. The highest pitch tone at that instant (averaged over a one-second interval) would give the maximum rocket speed.

The next step would be to try to collect other data like temperatures and pressures. This can be done if we modulate the transmitter with a number of tones and make each tone vary with the quantity we want to measure. Note that this means we must have small audio oscillators capable of having frequencies controlled with potentiometers, by variable capacitors, inductors, or by means of a voltage.

The procedure would be: First, calibrate the audio oscillator and set up a chart as shown in Table 6—1 (we assume that what we are to measure can be converted into an angular change).

Table 6 — 1

Audio oscillator and potentiometer calibration	
Potentiometer wiper position	Tone (cps)
Centered	600
10 degrees right	650
20 degrees right	700
30 degrees right	750
10 degrees left	550
20 degrees left	500
30 degrees left	450

We must be certain that the temperature and vibrations of the rocket will not cause changes in these calibrated figures.

Next, place the transmitter, modulator and oscillator in the rocket. Connect the potentiometer to, say, a fin shaft in such a way that, when

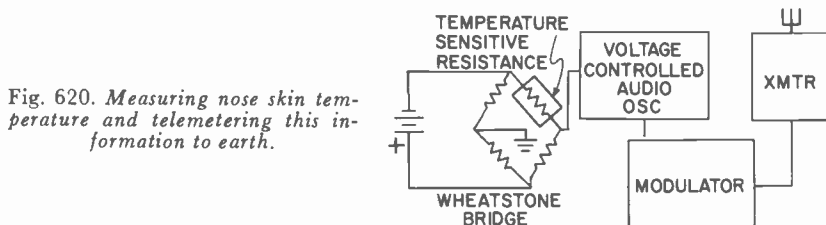


Fig. 620. Measuring nose skin temperature and telemetering this information to earth.

the fin is neutral, the arm of the potentiometer is centered. We launch the rocket, receive the modulated signal on our receiver, and pass this signal through a discriminator tuned to a rest frequency of 600 cps. The output of the discriminator is recorded on a moving chart.

If the fin is turned, we can tell from the lines made automatically on the chart how fast and when it turned. Thus, we can

measure physical variations of the rocket while it is in flight. We could use different tones to transmit many channels of information.

Fig. 620 shows how a voltage-controlled oscillator can be used to measure the rocket nose temperature. In this case, the oscillator would be calibrated in terms of the bridge unbalance per degree of temperature.

As in radio control, there should be frequency separation between the bands of frequencies used for telemetry purposes. For example, we used the band 450 to 750 cps for the fin measurement. Now we want to jump up the scale a little, say to 1,000 to 1,500 cps, for a band measuring nose temperature. The separation of the bands makes the

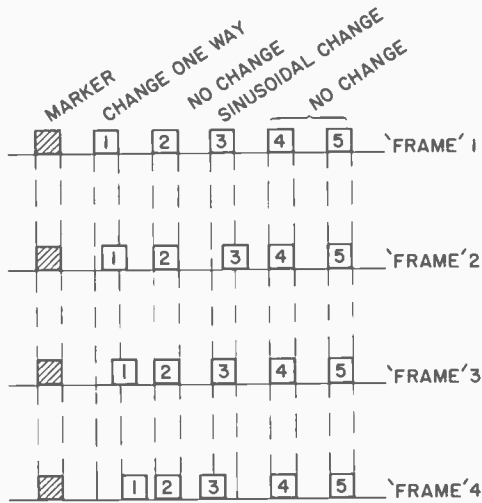


Fig. 621. Pen-recorded tape cut into frames for analysis.

decoding problem easier and more accurate. In the case of multiple tones or bands, we would have to feed the receiver output through bandpass filters before sending it to various discriminators.

This method of telemetry is called continuous because all information is sent back all the time. From the discussion of radio control systems using tones, remember that it is not wise to send more than 6 or 8 tones simultaneously because of the modulation percentage allotted to each. That holds true also for this system.

When we want to get more information, say from 30 to 120 channels at a time, we use pulses and pulse trains to do the job. The modulation percentage is 100 percent for each pulse, and the speed of transmission is so high that it is almost like getting continuous

information. Whatever we measure should be sampled at least seven times per second. This is the minimum number of samples needed for accurate reconstruction of a sine wave-like variation. In case the measured quantity is not expected to be a sine-wave function, it will be necessary to take more samples per second in order to reconstruct an accurate curve.

The method of using pulses is also very similar to that in radio control. Pulse width, amplitude, or spacing variations can be used to convey the intelligence. Fig. 621 shows how a tape might look which contains four frames (a frame is a complete pulse train), and how each pulse might be varied in time. The vertical lines then, through the same numbered pulses, show the variation in the measured quantity.

### Propulsion

The rocket engine furnishes the power which drives the rocket or missile into space. There are many types of jet propulsion devices. Let us examine some basic principles of rockets, both the solid and liquid propellant types.

There are two general types of solid fuel rockets, the restricted burning and the unrestricted burning types. In the restricted burning method, the propellant is ignited on one end only (Fig. 622-a) and

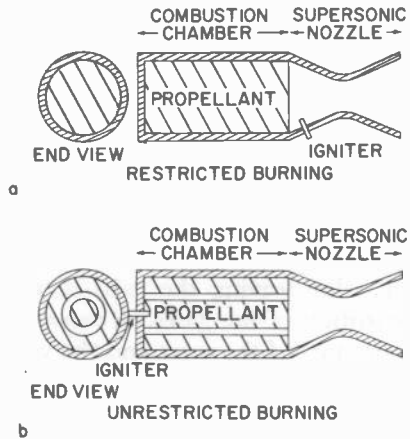


Fig. 622. Solid-propellant rockets.

the fuel burns like a cigarette. This type gives thrust for a longer time than the unrestricted burning method.

In the unrestricted burning type rocket, the fuel, which is cast in solid form, is molded or slotted (Fig. 622-b) so that it burns throughout its length. This type of rocket produces a much higher thrust (or push) for a much shorter period of time.



Every rocket engine has a nozzle. This is the tapered and flared exhaust section shown in Fig. 623. The nozzle has converging and diverging sections; these tapers are very important in getting the most power from the rocket. The converging section causes the gas velocity to increase until sonic speed (the speed of sound) is reached at the throat. The diverging section further increases the velocity by allowing the gases to expand rapidly out into the atmosphere. The expanding gas at the exit can reach a velocity higher than 2,000 feet per second.

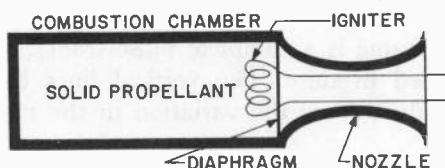


Fig. 623. *Typical rocket motor or engine.*

There is a popular belief that the rocket produces thrust when the exhaust gases push against the air. This is not true, because the rocket can operate in a vacuum and in space. What actually happens is that the mass of gases pushed out of the rocket combustion chamber at high speeds causes a reaction on the rocket. This reaction is what produces the thrust.

A simple example of the force produced by such a reaction is the kick of a shotgun against one's shoulder when the lead pellets fly out the barrel (Fig. 624). Another way to show the effect of reaction is to put on a pair of roller skates and throw some heavy rocks or bricks forward. Your effort in throwing the bricks forward will produce a reaction that will move you backward. The important point in the rocket is that, even though the gas molecules are very small and have very little mass, they move at such tremendous velocities that large reactions are produced.

The *thrust* ( $F$ ), then, is obtained by increasing the velocity ( $V$ ) of the gases from a zero value inside the combustion chamber to a very high value leaving the exhaust nozzle. This is called increasing the momentum of the gases. *Momentum* is the quantity of motion and is the product of the mass and the velocity ( $V$ ) of the gases. The *mass* of an object is its weight divided by the gravitational constant 32.2.

The rocket-thrust equation can be written:

$$F = \frac{(\text{Momentum at exit}) - (\text{Momentum in chamber})}{\text{time to move from chamber to exit}}$$

or

$$F = \frac{(\text{Mass} \times \text{exit velocity}) - (\text{mass} \times \text{chamber velocity})}{\text{time}}$$

or mathematically:

$$F = \frac{W}{g} \times \frac{V_e}{t} = \frac{W \times V_e}{g \times t}$$

Where  $W$  is the weight in pounds,  $g$  is 32.2,  $t$  is time in seconds and  $V_e$  is the gas exhaust velocity in feet per second. The part of the equation  $\frac{W}{t}$  is the amount of propellant burned per second.

Now an example to clarify the thrust equation: Assume that we have a propellant weighing 10 pounds and that this particular pro-



Fig. 624. *Action equals reaction.*

pellant, when burned in a combustion chamber which has a proper nozzle, produces an exhaust-gas velocity of 1,000 feet per second. Assume also that this burns 5 pounds of fuel per second. What is the thrust produced?

$$F = \frac{5 \text{ (pounds)}}{1 \text{ (second)}} \times \frac{1}{32.2} \times \frac{1,000 \text{ (ft/sec.)}}{1}$$

$$F = \frac{5,000}{32.2} = 155.28 \text{ pounds of thrust for 2 seconds}$$

Since we have 10 pounds of fuel and burn only 5 pounds per second, the engine will burn for 2 seconds. If we increase the burning rate (pounds per second) the thrust will increase, but last for a shorter time. Conversely, if we decrease the burning rate the thrust will decrease, but last for a longer time.

### Chemical reactions

Since the energy which propels the rocket comes from chemicals, let us analyze chemical reactions, particularly the reaction of zinc and sulfur, which we will use as the propellant in the rocket we design in the next chapter.

The energy which propels the rocket comes from a chemical reaction, or from the burning of chemicals. This process releases energy in the form of heat. The heat in turn produces kinetic energy, which is the energy of motion.

One simple chemical reaction which produces heat is the combustion of hydrogen ( $H_2$ ) and oxygen ( $O_2$ ) to form water plus heat. There is a way to show this reaction by means of symbols in an equation:



The arrow indicates that the hydrogen molecule plus the oxygen molecule change to water ( $2H_2O$ ) plus heat.

Perhaps you recall mixing an electrolyte, using distilled water and sulfuric acid. When the acid was poured into the water the mixture also developed heat. This is another chemical reaction which produces heat.

Another heat-producing process, not normally thought of as combustion, is the reaction between zinc ( $Z_n$ ) and sulfur ( $S$ ) to form zinc sulfide ( $Z_nS$ ). This can be stated as a chemical equation:



This is the basis of the propellant we will use in our model rocket design problems.

### Proportion of powders

We will use two powders, zinc and sulfur. To know how much of one to mix with the other, we must apply the law of balanced chemical equations.

We must determine the formula weights of the chemicals to be used. The formula weight is equal to the sum of the weights of the atoms indicated by the formula. The atomic weight of zinc is 65.38 and that of sulfur 32.07.

Now we also know something else from the chemical law. In the case of the combination of hydrogen and oxygen to form water plus heat, 2 atoms of hydrogen combine with 1 atom of oxygen, as denoted by the 2 in front of the hydrogen symbol. In the present case, 1 atom of zinc will combine with 1 atom of sulfur to produce the zinc sulfide and heat. We know this because there are no numbers in front of the parts of the equation. The formula weight then is:

The number of atoms of zinc times the atomic weight of zinc, plus the number of atoms of sulfur times the atomic weight of sulfur. The formula weight can now be stated symbolically as:

$$\text{Formula weight} = (1 \times 65.38) + (1 \times 32.07) = 97.45$$

This means that we want the same ratio for any amount of pro-

pellant as the ratio we would get by mixing 65.38 pounds of zinc with 32.07 pounds of sulfur for a total of 97.45 pounds of zinc sulfide propellant.

We will not usually want a quantity as large as 97.45 pounds. We want to know the proportions of zinc and sulfur needed to mix, say, 1 pound of propellant. The formula is:

$$\frac{65.38}{97.45} + \frac{32.07}{97.45} = 1 \text{ pound of propellant}$$

or for a more practical amount:

$$0.67 \text{ pounds zinc plus } 0.33 \text{ pounds sulfur} = 1 \text{ pound propellant}$$

If we want more propellant, we can now multiply these two numbers (0.67 and 0.33) by the number of pounds of propellant we want. If we want 10 pounds of propellant we would have to mix 6.7 pounds zinc with 3.3 pounds of sulfur.

Another useful thing to know is the ratio by weight of one chemical in the formula to the other. We find this by dividing the larger number by the smaller:

$$\text{Ratio} = \frac{65.38}{32.07} = 2.04$$

This means we always use 2.04 parts by weight of zinc to each part of sulfur.

## Liquid propellant rockets

To overcome weight and cooling problems for long-duration units, liquid propellants are used. In most liquid propellant rockets, one of the propellants enters the rear of the engine, flowing between the walls, cooling the inner surface, and making thin-walled combustion chambers possible.

In the process of flowing through and cooling these surfaces, the propellant itself is heated; it then enters the forward end of the combustion chamber.

This is known as regenerative cooling. Heating the propellant results in more efficient combustion and because the engine is cooled, long-duration burning is possible. The operating pressure in the combustion chamber is only 250 to 500 pounds per square inch (psi), and since the propellants are stored outside the combustion chamber, the construction may be lighter in weight than comparable solid propellant rockets (considering those beyond a certain impulse or power).

## Propellant systems

Two methods are used for supplying the rockets with fuel and an oxidizer from tanks. These are the pressure feed system and the pump feed system (Fig. 625).

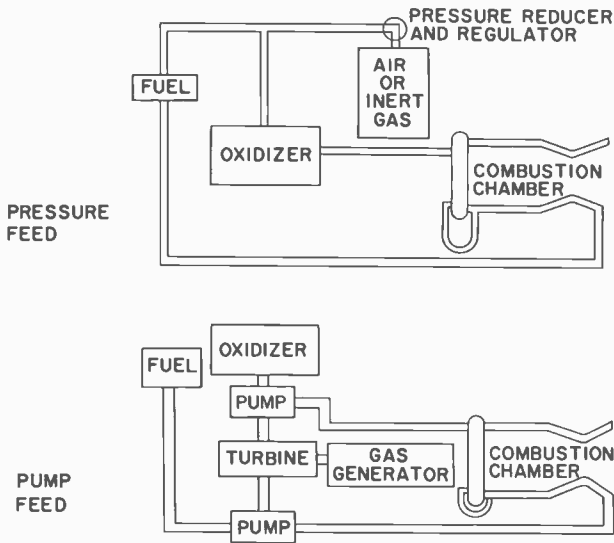


Fig. 625. *Liquid-propellant rockets.*

The pressure feed system is the less complicated of the two. Pressure is supplied to both the fuel and oxidizer tanks. The pressurized air (or an inert gas such as helium) is fed through a reduction valve to the two tanks at a pressure of about 500 psi, when the chamber pressure is approximately 300 psi. (As a rule of thumb, the pressure on the propellant tanks must be about 200 psi greater than the operating pressure in the combustion chamber.) To supply pressure for the duration of burning, which may be as long as 50 to 60 seconds, the pressure tank is originally charged to at least 150 atmospheres (about 2,200 psi). With a pressure of 500 psi or greater on the propellant tanks and 2,200 psi in the air bottle, these tanks must be of heavy construction. As the size of the rocket increases, the impulse-weight ratio decreases, until finally the empty weight of a pressure-feed rocket becomes a serious disadvantage compared to the empty weight of a pump-feed liquid rocket with the same impulse. This condition is reached at about 5 tons. However, the pressure-feed system is the more economical of the two for light-weight rockets.

In the pump-feed system, hydrogen peroxide may be combined with sodium permanganate as a catalyst in a gas-generating system. Combining in the reaction chamber, they generate steam, which is used to drive the turbine, which in turn drives the two pumps. Pressure is felt only on the downstream lines. Consequently, the fuel and oxidizer tanks can be of much lighter construction. The pump-feed system is far more complicated than the pressure-feed system, but there is a great weight saving, since there are no large air bottles and since thick-walled fuel and oxidizer tanks are not necessary. Another method is to place a small turbine in the exhaust jet, which drives the pumps, which in turn give the necessary pressure on the

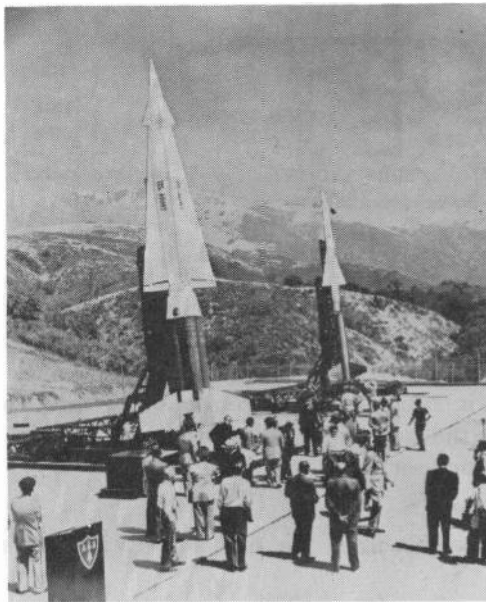


Fig. 626. *Hercules and Ajax rockets use liquid propellants.*

fuel and oxidizer lines. The Army Hercules and Ajax rockets are examples using liquid propellants (Fig. 626).

### **Atmospheric jets**

Two of the undesirable characteristics of rockets are short burning time and high rate of propellant consumption. To remedy these disadvantages, the pulse-jet, ram-jet, and turbo-jet utilize atmospheric oxygen (air) and carry fuel only.

## Pulse-jet

Fig. 627 shows the cross section of a typical pulse-jet. It consists of a tubular section, with a set of spring-loaded valves and a means for injecting fuel, followed by a combustion chamber and a tailpipe.

At the start of the operating cycle, the fuel is sprayed into the combustion chamber and is then ignited by a spark plug. The gases formed by combustion create a pressure of 25 to 35 psi. The spring-loaded valves prevent the gases from escaping through the intake so they rush out the tailpipe at high velocity, thus overexpanding and causing a partial vacuum inside the combustion chamber. This makes the valves open and draw fresh air into the combustion chamber.

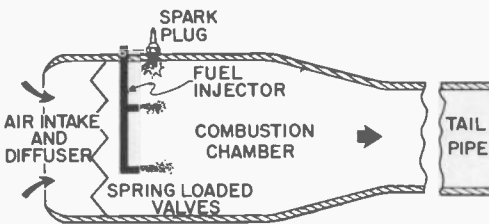


Fig. 627. Pulse-jet.

Part of the exhaust gases flow back up the tailpipe and meet the air coming in through the valves, which slightly compresses the new air. This compression, plus residual burning vapors, ignites a new charge of fuel, which is being sprayed continuously into the combustion chamber. Thus the action is intermittent, giving rise to the name intermittent jet, pulse-jet.

## Subsonic ram-jet

Assume that the *ram-jet* in Fig. 628 is operating at a speed less than

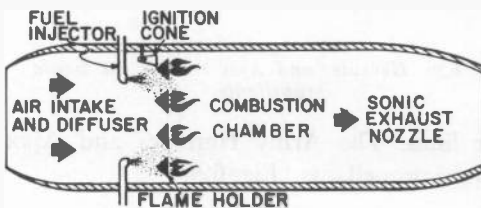


Fig. 628. Subsonic ram-jet.

the speed of sound. Air will flow through the ram-jet, which consists of a tubular section, with a diverging forward section or diffuser. As

air flows through the tubular section, it loses velocity, since the cross-sectional area increases.

The energy in the air stream is in the form of pressure energy and velocity energy. If the velocity decreases, the pressure must increase to keep the total energy constant. This is exactly what happens in the ram-jet; this increases the pressure, and makes the pressure at the forward end of the combustion chamber greater than the pressure in the free stream. Fuel is continuously injected into the air in the diffuser. The ignition cone, which is similar to the pilot light on a gas stove, maintains an ignition flame. The air-fuel mixture passes through the flame holder, which is a gridwork of V-shaped metal troughs. Part of the mixture swirls into the troughs and is ignited there by the ignition cone. The major portion of air and fuel passes on through the flame holder, which sets up a turbulence helpful for good mixing. It is ignited by the burning mixture in the flame-holder troughs. Combustion continues while the flow moves back through the combustion chamber.

The combustion gases want to expand in all directions, but are restricted by the combustion-chamber walls and the high-pressure area at the rear of the diffuser. Consequently, the gases are accelerated out the tailpipe. This is reaction and the thrust, which is also applied internally to the diffuser section.

### Supersonic ram-jet

The supersonic ram-jet (Fig. 629) works essentially in the same way as the subsonic ram-jet. The major differences are in the diffuser and exhaust sections.

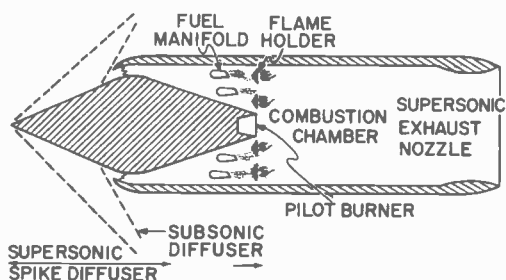


Fig. 629. *Supersonic ram-jet.*

The diffuser is a protruding conical spike. The spike aids in the pressure recovery (the process by which velocity energy is exchanged for pressure energy) (Fig. 630-a).

When the ram-jet has been boosted to a supersonic speed, it is



necessary to reduce the flow of air into the chamber to a subsonic velocity. A shock wave must be formed. If the subsonic type of diffuser is used, a normal shock wave will be formed; that is, one perpendicular to the flow of air.

A normal shock wave has two important characteristics; a large percentage of the flow of energy in a strong shock wave is dissipated as heat and the flow behind the shock wave is always subsonic. To realize a more efficient conversion of the flow energy the supersonic or spike diffuser was developed. By first changing the direction of flow, a conical shock wave is created which lowers the velocity (though not necessarily to a subsonic value), and is much more efficient in the conversion of flow energy to pressure than the normal shock wave. After passing through one or more conical shock waves, the air passes through a weak normal shock wave and enters the subsonic diffusion area. Thus a relatively high compression is realized and energy losses are minimized (Fig. 630-b).

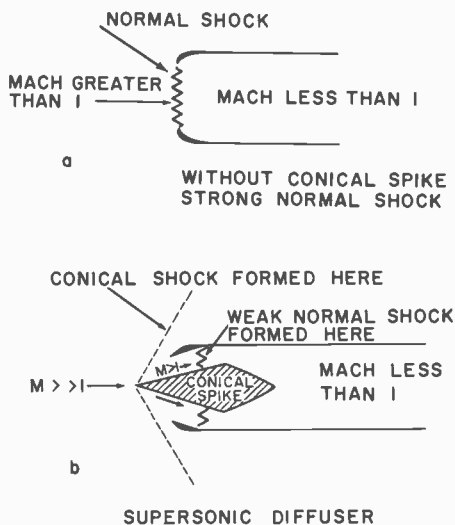


Fig. 630. Shock waves for supersonic diffuser.

After compression the fuel is added and the burning takes place downstream from the flame holder in the combustion chamber, exactly as in the subsonic ram-jet.

## Turbo-jet

The most common jet engine is the turbo-jet. It is possible to use this jet engine in aircraft because it is capable of developing sufficient

static thrust to let the aircraft take off under its own power.

The turbo-jet operates on the same principle as any other atmospheric jet engine. A quantity of air must be taken in and compressed and fuel added. The mixture burned in a combustion chamber expands and these products of combustion are accelerated rearward with increased momentum.

The turbo-jet consists of a compressor (which may be either axial (Fig. 631) or centrifugal (Fig. 632)), a combustion chamber, a method

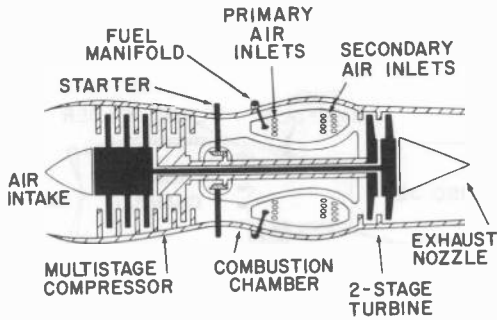


Fig. 631. Axial flow turbo-jet.

of introducing fuel, an exhaust for accelerating the combustion products and a turbine just ahead of the exhaust to extract power for driving the compressor. To start operation, the compressor must first

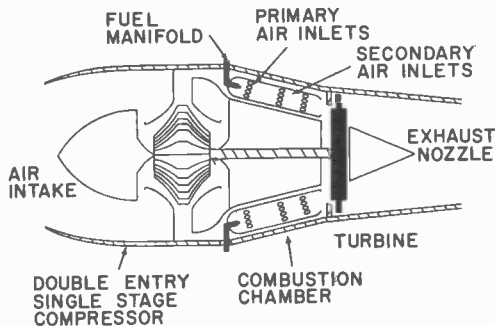


Fig. 632. Centrifugal flow turbo-jet.

be brought up to nearly 20 percent of normal operating speed to raise the pressure in the combustion chamber so that combustion can be accomplished. Fuel is then injected into the combustion chamber and ignited. Since combustion produces a temperature high enough to

ruin the turbine blades, secondary air is introduced, which lowers the temperature of the jet stream to about  $1500^{\circ}\text{F}$  before this stream reaches the turbine blades which are on the same shaft as those of the compressor. Hence, the hot-high-velocity gases passing through the turbine cause it to rotate, imparting rotation to the compressor.

### Turbo-jet with afterburner

The afterburner is a thrust-increasing device that mixes the unused air (oxygen) in the turbo-jet exhaust with other fuel, producing more thrust. The afterburner is nothing more than a subsonic ram-jet attached to the turbo-jet (Fig. 633).

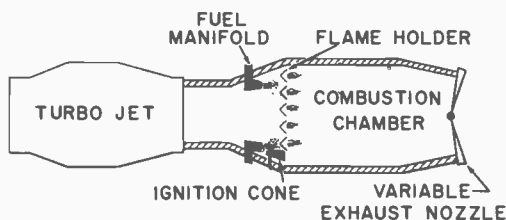


Fig. 633. Turbo-jet with afterburner.

The hot exhaust gases of a turbo-jet in operation have an excess of air. To utilize this air an afterburner consisting of diffuser section, fuel injection device, flame holder, combustion chamber, and exhaust nozzle is attached to the exit of the turbo-jet. After diffusion, more fuel is injected and the mixture is burned again. This results in a temperature much higher than the  $1500^{\circ}\text{F}$  which was the maximum allowable in the turbo-jet. Energy is added in the form of fuel, converted to thermal energy, and finally converted to kinetic energy by reaction. This added thrust increases the momentum of the mass as it passes out of the afterburner exhaust nozzle. While the afterburner is operating, the variable exhaust nozzle is opened to prevent the temperature and pressure from backing up into the turbo-jet. An increase in thrust of about 40% is realized with afterburner operation. Fuel consumption increases approximately 250%. Because of the increased use of fuel, the afterburner is used only when extra thrust is needed.

# model rocket design and construction

## chapter 7

Now we will show the calculations which must be performed to design a model rocket. Methods of construction, ways of launching and firing will also be discussed. The calculations are not difficult and an effort has been made to make them as clear as possible.

A model rocket is *not a toy*. It is a most dangerous instrument when treated lightly. We shall first devote a few words to that all-important topic of safety.

### **Safety precautions**

Most states and many municipalities have enacted legislation banning the sale, manufacture and firing of fireworks by unlicensed persons. Rockets and rocket fuel are similar to fireworks in many respects, so it is important that anyone who plans to venture into amateur rocketry learn about local laws so that all activities can be conducted on a legal basis.

When rockets are transported on state highways they must be handled in accordance with the laws of that state and the laws governing interstate commerce. It is best to consult your state highway patrol or similar organizations for this information.

When rockets loaded with propellant are transported on a military reservation, the igniter must be packaged separately. The transporting vehicle must be clearly marked *explosives* on the front and rear sides. Each vehicle must be equipped with two fire extinguishers.

Because a rocket can present a hazard to air navigation one should also think of the possibility of legal problems which may be encountered. In general, the rocket must be fired into an airspace from which aircraft are restricted, or clearance must be obtained from the Civil

Aeronautics Authority. In any event, remember that even the airspace is regulated and cannot be used indiscriminately.

Before entering into any type of amateur rocket activity either in a group or as an individual, it is advisable to secure expert legal guidance concerning your liability responsibilities as to property damage, injury or death to live stock. Injury, even to an *uninvited* spectator trespassing on your own private firing range, could result in costly and unpleasant court action.

Do not experiment with model rockets without proper supervision and guidance. Students can often enlist the aid of a teacher who, in turn, can contact military agencies and obtain guidance and assistance from persons and agencies who are experts and engaged professionally in the handling of rockets. *Do not take chances. Plan. Take extra precautions. Get help from experts. Enjoy this hobby and live!*

### **Handling of propellants**

The zinc and sulfur micrograin propellant is the best type for amateur rockets on the basis of both performance and safety. The following rules should be rigidly adhered to in its handling:

1. Handle and mix only under direct, expert supervision.
2. All equipment used in mixing must be connected to an electrical ground to guard against accidental sparks from static electricity. An electrical ground connection may be made to a water line or a metal rod driven into the earth. All metal parts must be connected (bonded) together by flexible wires which are connected to the ground. The ends of the wires should be bright and clean and all connections tight and incapable of being loosened by accident.
3. Allow no open flames or sparks in the mixing area.
4. Do not heat or cook mixtures.
5. Do not grind or apply heavy pressure or subject mixture to shock.
6. Do all mixing out of doors.
7. Do not allow excessive micrograin dust to accumulate in the air.
8. Allow only the minimum number of essential people near the mixing and loading operations or near the loaded rocket.
9. Handle as small a quantity of propellant as possible.
10. Mix the propellant near the launching site.
11. Do not load rocket until ready to fire.
12. Wear flame-resistant and protective clothing.
13. Have fire-fighting, rescue and first-aid equipment standing by during all propellant-handling operations.



Fig. 701. Guided missile being loaded with liquid fuel.

Fig. 701 shows the loading of a guided missile with liquid fuel. Note the protective clothing worn. Fuel is carefully measured before being pumped into the rocket-fuel tank.

### **Dangers of other propellant types**

Most other types of propellants are considered too dangerous to be handled by amateurs or hobbyists. This applies especially to the readily available chlorates like sodium chlorate and potassium chlorate. These explode very easily when rubbed, ground or mixed — they are not even used in military or scientific rockets!

The dust of powdered metals such as iron, magnesium, nickel and aluminum can form explosive mixtures with air when poured from one container to another, or when shaken. The dust of some of these metals can ignite spontaneously while floating in the air. When these metals are mixed with an oxidizer they become sensitive to shock. (An oxidizer furnishes oxygen to the mixture.)

Most people know that nitroglycerine will explode violently on slight shock, and is sensitive to heat. Nitrocellulose can also explode when subjected to heat or shock and it burns easily in the open air when ignited. Metallic sodium, metallic potassium and yellow phosphorus all ignite spontaneously when exposed to air. Liquid propellants

generally present additional hazards such as poisonous fumes, extreme corrosion and spontaneous ignition.

### **Rocket firing operations**

Firing of rockets should be confined to approved firing ranges and conducted under the supervision of qualified individuals. Firing procedures should be carefully and painstakingly thought out, and written out, step by step, in advance of the firing. The procedure should be checked by experts, practiced with an unloaded rocket until letter perfect and then carefully followed in the actual firing.

The rocket ignition system should not be connected until just before firing and should always be of a type that can be activated electrically from the safety of a distant bunker. The connecting of the firing mechanism should be one of the very last steps performed, and should be done only when all personnel are in a place of safety.

All persons connected with the firing should be in safety bunkers with overhead protection when the rocket is fired. A rocket should never be launched exactly vertically nor should it be launched during a strong wind. The rocket when fired exactly vertically endangers the launching site — it may not go as high as expected — it may explode just overhead and fall back on the launching crew. Strong winds can cause the rocket to go off course and endanger persons or property.

In the event of a misfire (the rocket doesn't go off when the firing switch is closed) try to fire it a minimum of three more times. If it still doesn't fire, wait at least thirty minutes before approaching the rocket. Disconnect all wires to the firing device before approaching. After a successful firing everyone should remain under cover until it is certain that the rocket has returned to earth.

### **Safety summary**

The rocket hobby, while enjoyable, can also be a life-and-death matter. Use only a recommended propellant. Design the rocket with the greatest care so that it has the best chances to perform as expected. Static test (ground fire) the rocket before launching. Observe all the safety precautions mentioned earlier. After the rocket has been static tested, load the propellant and connect the igniter only at the site of the actual launching after being certain that the static firing has caused no weakening of the structures. Expose a minimum number of people to the loaded and armed rocket. By using extreme caution and care you can have a successful and safe firing. You can make your rocket hobby a gratifying, worthwhile experience instead of a tragedy.

## Costs and equipment

A single rocket about two inches in diameter and four feet long will cost about \$35.00. The propellant, mixing and ignition system will cost about \$40.00 additional. Much of the launching equipment can be made and then used over and over again. Sometimes the rockets themselves can be recovered by means of parachutes and, if they remain sound, can be used again.

Stop watches, movie equipment and some electronic equipment will be needed to give purpose and meaning to this hobby. These are best obtained through a club effort. If a club is formed, costs can be shared. Often guest speakers can be obtained for meetings and time can be spent studying designs between the actual launching activities. Learn as much as you can about the theory of the devices involved. Set specific objectives for each launching to increase the knowledge of the club members. A lifetime career in space technology may well start from this beginning.

## Design of a model rocket

We will now show how to design a model rocket to meet the following specifications:

- a. To have a thrust of 800 pounds for 0.5 second.
- b. To use zinc and sulfur as the propellant.

The procedure is as follows:

- a. Determine the amount of propellant needed.
- b. Determine the diameter of the burning surface.
- c. Determine the length of the propellant.
- d. Determine the thickness of the combustion chamber walls.
- e. Determine the dimensions of the exhaust nozzle.

There are certain other bits of information which are needed for the design, especially those concerning the propellant. These can be calculated but the mathematics are beyond the scope of this text. Instead we will just state these as facts and use them in our design. Remember, the factors in Table 7—1 apply to the zinc-sulfur propellant only.

Table 7—1

### Characteristics of Zinc Sulfur Propellant

a. Effective exhaust velocity ( $V_e$ )	= 1490 lbs/ft/sec.
b. Chamber pressure ( $P_c$ )	= 1,000 lbs/sq. in.
c. Chamber temperature ( $T_c$ )	= 3060° Rankine
d. Molecular weight ( $M_w$ )	= 97.45 lbs/mole
e. Specific heat ratio ( $\gamma$ )	= 1.25
f. Density (D)	= 161 lbs/cu. ft. = 0.0932 lbs/cu. in.



- g. Burning rate (r) = 90 in./sec.  
 h. Gas constant (Particular) = 15.8 ft/degree Rankine  
 i. Thrust coefficient ( $C_r$ ) = 1.57

As a point of information, some temperature conversion factors are:

$$\begin{aligned} \text{Rankine} &= F + 460^\circ \\ \text{Kelvin} &= C + 273^\circ \\ \text{Centigrade} &= 5/9 (F - 32^\circ) \end{aligned}$$

*Solution:*

The weight of the propellant ( $W_p$ ) required can be found by using the thrust equation:

$$F = \frac{W}{gt} \times V_e \quad \text{or} \quad F = m \times V_e$$

where  $m$  is the mass of propellant burned per second.

For our problem we rewrite the equation:

$$F = \frac{W_p}{t_b \times g} \times V_e$$

where  $W_p$  is defined above,  $t_b$  is the burning time and  $g$  is the gravitational constant 32.2 ft/sec<sup>2</sup>. Then:

$$W_p = \frac{F \times t_b \times g}{V_e}$$

and inserting the values for these letters,

$$W_p = \frac{800 \times 0.5 \times 32.2}{1490} = 8.64 \text{ lbs. of propellant required}$$

Remember that we are using a ratio of 2.04 parts of zinc and 1 part of sulfur (3.04 part total) so the proper weights of each will be:

$$\text{Weight of zinc} = \frac{2.04}{3.04} \times 8.64 = 5.80 \text{ lbs of zinc powder.}$$

Weight of sulfur can be either 8.64 — 5.80, or 2.84 lbs, or can be calculated by using the ratio:

$$\text{Weight of sulfur} = \frac{1}{3.04} \times 8.64 = \text{lbs of sulfur powder.}$$

### **Weight of propellant burned per second**

To determine the proper shape of the propellant we must determine the burning rate. We want all propellant burned in 0.5 second and we

know how many pounds of propellant are necessary, so the burning rate is simply:

$$\frac{\text{total propellant weight}}{\text{burning time}} =$$

$$\frac{8.64 \text{ lbs of propellant}}{0.5 \text{ second}} = 17.28 \text{ lbs per second}$$

### The burning surface

This can be determined easily since the volume of propellant burned per second equals the burning surface area ( $S$ ) times the burning rate ( $r$ ). The volume burned per second also equals the weight per second burned divided by the density ( $D$ ). From the above we can write two equations and using these, can find the burning surface and from that the diameter of propellant required.

$$(1) \quad V = S \times r$$

$$(2) \quad V = \frac{W_p}{t_b} \times \frac{1}{D}$$

We equate (1) to (2):

$$S \times r = \frac{W_p}{t_b} \times \frac{1}{D}$$

Inserting the numerical values known, or found previously, and solving this equation for ( $S$ ):

$$S = \frac{\frac{W_p}{t_b}}{r \times D}$$

$$S = \frac{17.28 \text{ lbs sec.}}{90 \text{ (in. per sec.)} \times 0.0932 \text{ lbs/in}^3}$$

$$S = \frac{17.28}{90 \times 0.0932} = 2.06 \text{ square inches}$$

So our propellant must have an end area of 2.06 inches.

Generally, the rocket chamber is in the form of a cylinder or pipe, so this square-inch end area becomes an equivalent circular area from which we can state the tube diameter. Since the area of a circle is

equal to  $\pi r^2$  or  $\frac{(\pi) (\text{diameter})^2}{4}$  all we have to do is to set this equa-

tion equal to 2.06 and solve for the diameter.

$$S = \frac{(\pi) (\text{diameter})^2}{4}, \text{ then}$$

$$\sqrt{\frac{4 S}{(\pi)}} = \text{diameter, and}$$

$$\sqrt{\frac{(4) (2.06)}{3.14}} = 1.625 \text{ inches}$$

So our rocket combustion chamber must have an inside diameter of 1.625 inches.

The length required is equal to the burning rate times the total burning time:

$$90 \text{ inches per second} \times 0.5 \text{ second} = 45 \text{ inches}$$

At this stage, then, we know in what proportion the propellant must be (zinc and sulfur), and the size of the combustion chamber (tube or pipe) that it will be put in. Next the thickness of the pipe walls must be determined. We don't want our rocket to blow up when we try to launch it.

The tensile strength of the materials to be used is our next concern. If we use a low-carbon steel for the propellant tube that has a tensile strength of 62,400 psi (SAE 1020) we divide that rating by four and assume that it can stand only 15,600 psi.

$$\frac{62,400}{4} = 15,600$$

This gives a safety factor of four. This safety factor is necessary because the extremely high temperatures that are generated by the burning propellant reduce the strength of the steel considerably.

The wall thickness is determined from the equation:

$$\frac{\text{chamber pressure} \times \text{radius}}{\text{allowable stress}}$$

The pressure inside the chamber was given as 1,000 pounds per square inch. The inside radius of the pipe is 0.81 inch, and the stress is the factor we computed above, 15,600 pounds per square inch. The wall thickness then is:

$$\frac{1,000 \times 0.81}{15,600} = 0.0519 \text{ inch}$$

A steel tube with a wall thickness of 0.0625 inch, about equal to 16 gage, will do nicely. The tube must have an outside diameter of 1.75 inches and an inside diameter of 1.625 inches will fulfill the requirement.

The final part of the rocket to be calculated is the nozzle. We must calculate the *throat-* and *exit-area* diameters (Fig. 702). These dimen-

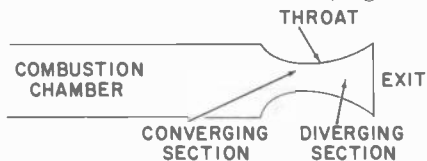


Fig. 702. DeLaval nozzle adapted for rocket engine.

sions are very important since they determine the maximum efficiency from the exhaust gases and thus maximum thrust.

Additional information is needed to make these calculations. This is given in Table 7—2.

Table 7—2  
Coefficient of Thrust ( $C_f$ )

Pressure ( $P_c$ ) psia	$\gamma$				
	1.15	1.12	1.25	1.3	1.4
600	1.15	1.52	1.50	1.48	1.46
700	1.58	1.54	1.52	1.50	1.48
800 - - -	1.60 - - -	1.56 - -	> 1.54	1.52	1.50
900	1.62	1.58	1.56	1.54	1.51
1,000	1.63	1.59	1.57	1.55	1.52
1,100	1.64	1.60	1.58	1.56	1.53
1,200	1.66	1.62	1.59	1.56	1.54
1,300	1.67	1.63	1.60	1.57	1.54
1,400	1.68	1.64	1.61	1.58	1.55

To find the value of  $C_f$  needed, we enter the table horizontally opposite 800 pounds (the thrust value initially assumed) to the column headed by 1.25, the value of gamma ( $\gamma$ ) given in Table 7—2. At the intersection we obtain the value 1.54 to use in the formula:

$$\text{Force} = C_f \times A_t \times P_c$$

First we must solve this formula for  $A_t$  and we get:

$$A_t \text{ (area of throat)} = \frac{F}{C_f \times P_c}$$

Our force (thrust) is 800 pounds, the  $C_f$  just determined is 1.54, and  $P_c$  was given earlier (Table 7—1) as 1,000 lbs/sq. in. Inserting these values in the equation and solving for the throat area:

$$A_t = \frac{800}{1.54 \times 1,000}$$

gives us 0.51 square inches as the answer.

To determine the diameter of the throat, we use the equation:

$$D_t = \sqrt{\frac{4}{\pi} \times 0.51} = 0.806 \text{ inch}$$

Next, then, is the diverging nozzle (Fig. 702). To obtain maximum thrust, we must calculate the exit area and its diameter. These will be larger than those at the throat. Our computation begins by referring to Table 7—3.

Table 7—3  
Nozzle Expansion Area Ratio

Pressure ( $P_c$ ) psia	$\gamma$				
	1.15	1.2	1.25	1.3	1.4
600	6.8	6.0	5.6	5.2	4.5
700	7.6	6.8	6.3	5.8	5.0
800	8.4	7.6	6.8	6.4	5.4
900	9.2	8.2	7.4	6.8	5.8
1,000	10.0	8.8	> 8.2	7.4	6.2
1,100	10.9	9.5	8.7	7.9	6.7
1,200	11.6	10.2	9.3	8.4	7.0
1,300	12.4	10.8	9.8	8.9	7.4
1,400	13.0	11.5	10.4	9.4	7.7

Glance down the first column  $P_c$  (chamber pressure) to 1,000 psia. This is the value of  $P_c$  which was given in Table 7—1. Go across that line to the column headed by a gamma of 1.25. This is also given in Table 7—1. At the intersection we find a ratio for the nozzle expansion area of 8.2.

The formula for determining the exit area,  $A_e$ , is:

$$A_e = 8.2 A_t$$

or 8.2 times the throat area. We found the throat area to be 0.51 inch so, using the formula above, the exit area is:

$$0.51 \times 8.2 = 4.18 \text{ sq. in.}$$

To find the diameter of the exit end of the nozzle, we again use the formula:

$$D_e = \sqrt{\frac{4 \times 4.18}{\pi}} = 2.31 \text{ in.}$$

We can now draw the nozzle showing the dimensions in Fig. 703. To determine the lengths of the converging and diverging sections

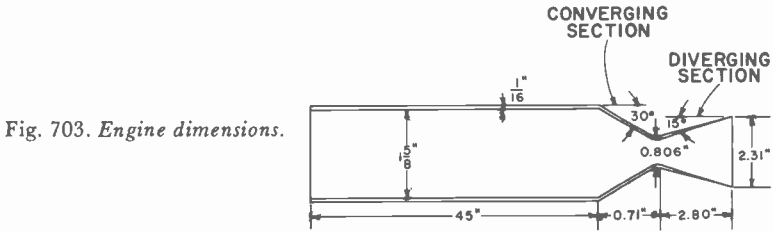


Fig. 703. Engine dimensions.

of the nozzle we have used a converging angle of  $30^\circ$  and a diverging angle of  $15^\circ$ . We use the equations:

$$L_c \text{ (converging length)} = \frac{0.5 (D_e - D_t)}{\tan 30^\circ}$$

$$L_d \text{ (diverging length)} = \frac{0.5 (D_e - D_t)}{\tan 15^\circ}$$

The numerical values  $D_e$  and  $D_t$  were found earlier. From a set of trigonometric tables,  $\tan 30^\circ$  equals 0.577 and  $\tan 15^\circ$  equals 0.268.

$$L_c = \frac{0.5 (1.625 - 0.806)}{0.577} = 0.71 \text{ in.}$$

$$L_d = \frac{0.5 (2.31 - 0.806)}{0.268} = 2.80 \text{ in.}$$

These are the dimensions shown in Fig. 703.

Now that we have completed our calculations, we find that we would use tubing 1.69 (or 1-11/16) inches O.D., .0625 inch thick with a converging angle of  $30^\circ$  and a diverging angle of  $15^\circ$ . The nozzle will have to be machined in one of the three patterns shown in Fig. 704. Note that it is then fastened in place in the tube, with machine

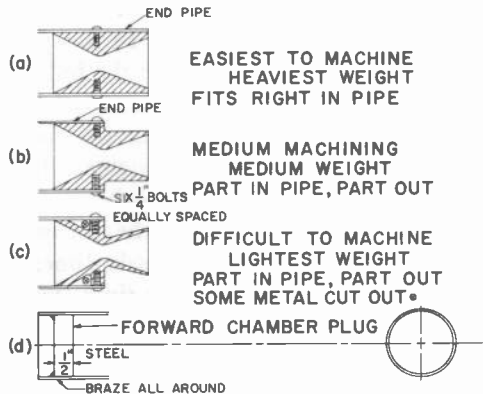


Fig. 704. Typical nozzle and plug constructions.

screws, at the right length from the plug at the other end. The plug (Fig. 704-d) should be a solid piece of 0.5-in. thick steel brazed into the tube end as shown. A rounded or bullet-shaped nose section of hardwood or metal could be fitted to this plugged end of the rocket

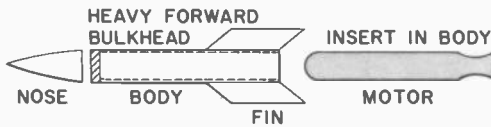


Fig. 705. *Motor and body as separate units.*

motor to form an aerodynamic shape, or the rocket motor might be fitted into a rocket body as shown in Fig. 705.

### Fins

The tail fins may be made from 1/16-inch thick steel or 1/8-inch thick aluminum and set equidistant around the body as shown in Fig. 706. The fins can be fastened by any of several methods (some are shown in Fig. 706) but this must be done before any propellant is added.

Use special care to get the fins exactly in line with the longitudinal axis of the rocket and mounted securely so that flutter cannot cause an erratic flight. Severe flutter can cause the rocket to break up. The width of the fins from tip to tip should not be over 200 times the fin thickness. This means about 20 inches for this rocket. The length may be from 18 to 24 inches. In general, the side-view area of the rocket with fins must be larger than the front area, on each side of the center of balance, for stability in flight.

### Design of a rocket motor when the tube is specified first

Before going ahead with the launching and firing, there is one additional problem in design. In this problem assume that you already have a length of steel tubing of the following dimensions:

- a. Wall thickness is 1/16 in.
- b. Outside diameter is 2 in.
- c. Inside diameter is 1-7/8 in. (1.875")
- d. Length is 4 ft.

and you want to determine the thrust, the burning time of the propellant in the tube and the nozzle dimensions.

To determine the burning time, we must know the burning area and the length of the propellant in the tube. If we allot 3 inches of tube length for the nozzle and nose sections, it will leave 45 inches of

the 48 for the propellant. The area of the propellant can be calculated from:

$$\text{Area} = S = \frac{\pi d^2}{4} = \frac{(3.14) \times (1.875)^2}{4} = 2.76 \text{ in.}$$

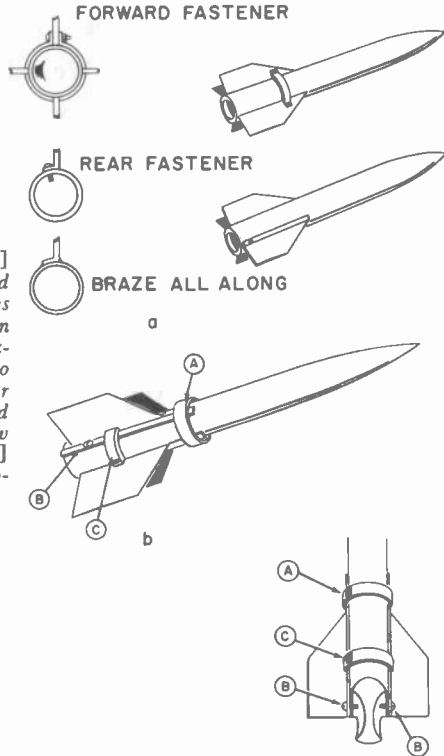


Fig. 706. Fin-assembly detail [a] and [b] "strap method" to avoid brazing to chamber or drilling holes except those to mount nozzle. In upper illustration [a], bolt into nozzle or motor extension but not into combustion chamber. In lower drawing [b], ring over forward end of tail. Braze to tail [A]. [B] Screw fasten end of tail to nozzle. [C] Braze straps between tail fins at approximate midpoint if desired.

The weight of the propellant to be burned per second will be:

$$\begin{aligned} &\text{Area} \times \text{burning rate} \times \text{density} \\ &2.76 \times 90 \times 0.0932 = 23.15 \text{ lbs/sec.} \end{aligned}$$

The burning time of propellant in the tube will be:

$$\text{Burning time } (t_b) = \frac{\text{length}}{\text{burning rate}} = \frac{45}{90} = 0.5 \text{ sec.}$$

Finally, to determine how much propellant is needed by weight, multiply the weight burned per second by the burning time:

$$23.15 \times 0.5 = 11.58 \text{ lbs of propellant.}$$



From this we determine the weight ratios of the zinc and sulfur propellant by:

$$\text{Zinc powder (lbs)} = \frac{2.04}{3.04} \times 11.58 = 7.77 \text{ lbs}$$

$$\text{Sulfur (lbs)} = \frac{1}{3.04} \times 11.58 = 3.81 \text{ lbs}$$

Now we can compute the thrust. We will obtain, using the formula:

$$\text{Thrust (F)} = \frac{\text{Weight of propellant burned per sec.} \times \text{Exhaust velocity}}{\text{Gravitational constant}}$$

$$F = \frac{23.15 \times 1490}{32.2} = 1071 \text{ lbs of thrust}$$

The area of the nozzle throat is determined in exactly the same manner as for our first example. Note that we must use a different row in Table 7—2 to get the thrust coefficient, 1.57.

$$A_t = \frac{1071}{1.57 \times 1,000} = 0.682 \text{ sq. in.}$$

The exit area of the nozzle, again using Table 7—2, is:

$$A_e = 8.2 \times A_t = 5.59 \text{ sq. in.}$$

The throat and exit diameters are then calculated as before:

$$D_t = \sqrt{\frac{4 \times 0.628}{3.14}} = 0.894 \text{ in.}$$

$$D_e = \sqrt{\frac{4 \times 5.59}{3.14}} = 2.66 \text{ in.}$$

Finally, to determine the lengths of the converging and diverging nozzle sections:

$$L_c = \frac{0.5 (1.875 - 0.894)}{0.577} = 0.85 \text{ in.}$$

$$L_d = \frac{0.5 (2.66 - 0.894)}{0.268} = 3.29 \text{ in.}$$

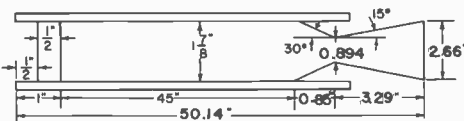


Fig. 707. Dimensions of chamber and nozzle.

We use exactly the same procedure as in the previous example with the same converging and diverging angles. It is suggested that on all nozzles the computed lengths be increased slightly so that the throat can be rounded. Do not make the lengths shorter. Rounding of the throat will add perhaps one-half inch to the length. Fig. 707 shows the dimensions of the rocket engine based on these computations. Again we have shown a 0.5-inch plug at the forward end which must be brazed in place.

### Ignition systems and launchers

There is only one safe, approved method of firing a rocket and that is by electricity. This allows the person firing the rocket to remain at a safe distance from the rocket launcher when the rocket is ignited. The principle of electrical ignition is not complex. A small piece of nichrome wire is heated by passing a large electrical current through it. This wire is mounted on a plastic or wooden plug (Fig. 708) just large enough to fit into the

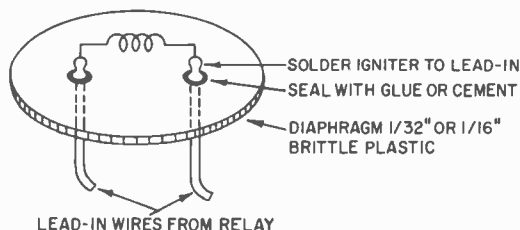


Fig. 708. *Typical igniter.*

nozzle end of the rocket and press against the propellant until the exhaust gases blow it out.

A relay system is necessary to pass a large current through the igniter wire (it must have short leads to it) and also to make remote operation of the igniter possible. This relay system with its battery, warning light and safety switch is the rocket ignition system. The relay can operate with a small current so we can run long wires to the ignition system from a distant bunker and fire our rocket motor from a safe position.

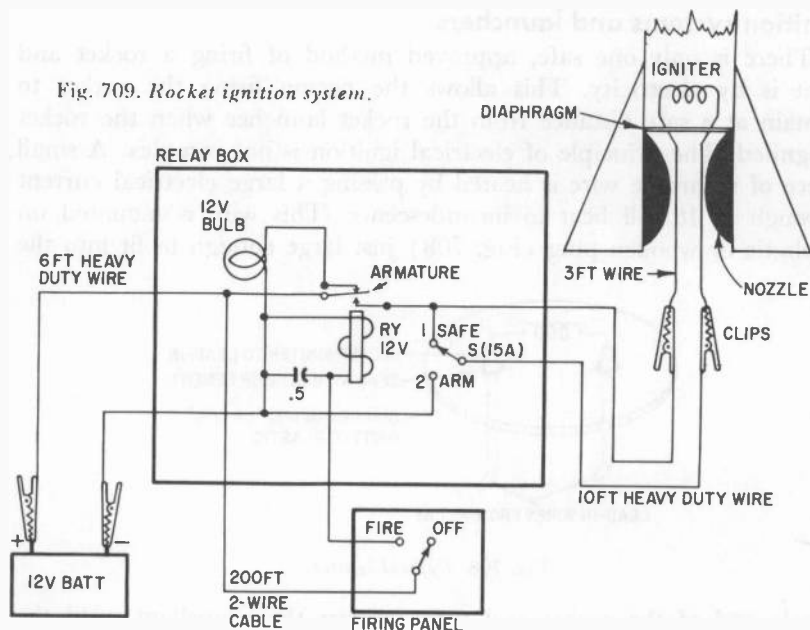
Always keep a short circuit across the igniter until the last moment before you are ready to fire the rocket. Never connect the igniter to the ignition system until the last moment before firing.

In the ignition system circuit shown in Fig. 709, starting at the right of the diagram, note that the leads of the igniter are connected through heavy wires to a switch (S) which is shorting the line to

the igniter. This is a safety short circuit. When we are ready to fire the rocket, the switch is moved down to position 2 so that the lower side of the line connects directly to the negative terminal of the 12-volt battery. The battery must be large enough to supply the heavy current required for good ignition.

The left wire from the igniter connects to the normally open relay contact. The relay is shown in the de-energized position. The armature of the relay is connected to the positive terminal of the 12-volt

Fig. 709. Rocket ignition system.



battery. The normally closed relay contact is connected to the positive terminal of the battery when the armature is de-energized and the warning light is connected to this contact. This will always indicate that the battery has been connected to ignition system. Be careful when this light burns!

The relay has a  $0.5 \mu\text{f}$  capacitor across its windings. This causes a delay in the releasing action of the relay to insure ignition even though the firing button is depressed only momentarily.

### Blast-off techniques

When the rocket is ready to fire the last person to leave the launching area will manually change the position of the safe-arm switch (S) to the arm position. This same person should be the only one who is authorized to depress the firing switch back at the bunker.

After closing the firing switch on the firing panel the rocket should blast off. If it does not, try three more times at five-minute intervals (if the battery is weak this will allow it to recover somewhat to give another current jolt to the igniter). If the rocket still does not fire, wait at least 30 minutes before anyone approaches it; then one person goes to the launcher and, first, moves the safe-arm switch to safe; next, disconnects the igniter wires; last, removes the igniter.

Check that:

- a. Firing switch is off
- b. Safety switch is at safe
- c. Rocket igniter wires are shorted (wrapped together)

A typical rocket launching count down or operations procedure is as follows:

17. Place rocket on launcher. Send all extra persons from rocket launch area.
16. Place relay box (ignition system) 10 feet from launcher.
15. Connect battery to ignition system.
14. Check that safety light is on.
13. Connect the firing panel to the ignition system.
12. Connect an extra igniter to the ignition system leads. Do not put this igniter in the rocket.
11. Place safe-arm switch to arm.
10. Operate the fire switch.
9. Check to see if the test igniter has burned through. This is a test of the firing circuit. If the igniter has burned through, go ahead with the next step. If not, check the firing system till it operates satisfactorily.
8. Turn fire switch off.
7. Place the safe-arm switch to safe.
6. Send all personnel but one from the launcher area. Other personnel should be at least 200 feet away and under cover.
5. Place the rocket igniter inside the rocket nozzle up against the propellant and unshort the leads.
4. Attach the relay box leads to the rocket igniter.
3. Place the safe-arm switch to arm.
2. The last man now goes to the safe area which is 200 feet away. He gets under protective cover.
1. This last man operates the fire switch.

**BLAST-OFF!**



Fig. 710. *Early model of Nike Zeus.*

When rocket is away, turn firing-control switch off. Wait to be sure the rocket has impacted before leaving shelter.

### **The rocket launcher**

We have discussed the firing procedure and launching but as yet have not discussed the actual types of launchers which can be used with small rockets. Fig. 710 shows an early model of the Nike Zeus. Note the structural strength and rigidity built into its launching arm.

Fig. 711 shows a Nike Hercules and in the almost vertically erect position a Nike Ajax. All three of these missiles are held in place on their launchers by a small clip or finger in such a way that they can be elevated or depressed, yet, when fired, a few inches of movement frees them from the launcher rail.

We can say that the rocket launcher has two purposes:

- a. To support the rocket till it is launched.
- b. To provide initial direction in guidance.

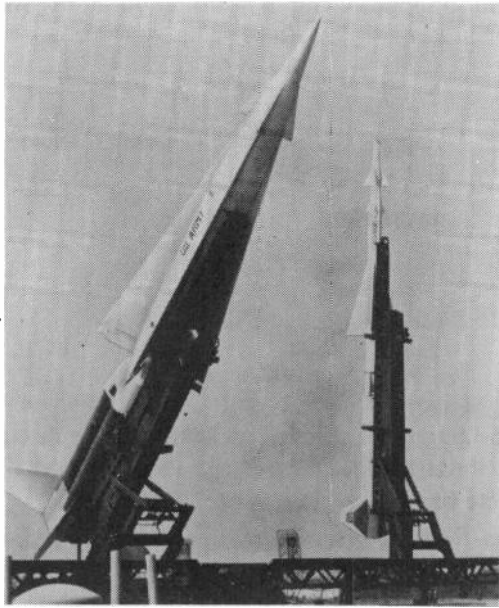


Fig. 711. Nike Hercules [left] and Nike Ajax.

There are three launching methods which are suitable. These are:

- a. The Ring over Pole.
- b. The Clip on Rail.
- c. The Slotted Rail.

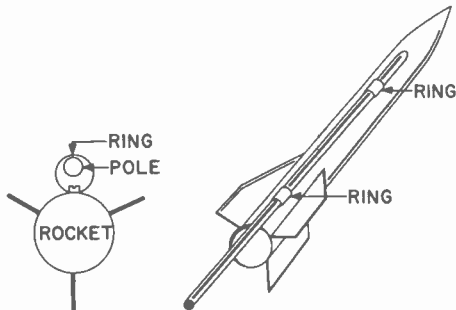


Fig. 712. Ring over Pole.

The three types are illustrated in Figs. 712, 713, 714.

The *Ring-over-Pole* type requires that the pole be securely fastened in a solid mounting base and be stiff enough to avoid bending or

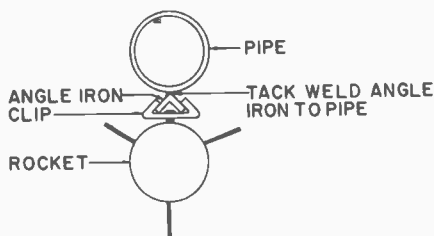


Fig. 713. *Clip on Rail.*

whipping. A  $\frac{3}{4}$ -inch steel rod and 1-inch rings on the rocket will usually be satisfactory for the size rockets we have discussed. Normally, the pole is inclined about  $5^\circ$  from the vertical, and should be solidly set in a concrete base.

The *Clip-on-Rail* type can be made of  $1 \times 1 \times \frac{1}{4}$ -inch angle iron, so arranged that the clip on the rocket body is able to grip the angle as shown in Fig. 713. The angle iron must be fastened to a piece of 2-inch pipe to get the required rigidity. This type of rail can be reinforced easily to prevent bending or whipping when the rocket is in motion.

The *Slotted Rail* (Fig. 714) may be constructed by welding together four pieces of  $\frac{3}{4} \times \frac{3}{4} \times \frac{1}{8}$ -inch angle iron. The standing

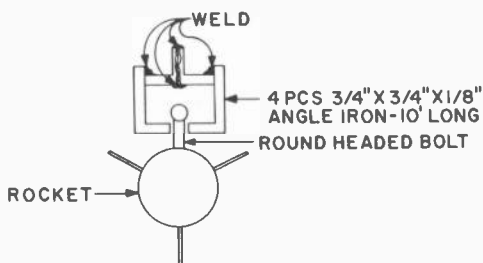


Fig. 714. *Slotted Rail.*

legs of two of the angles are welded back to back, forming a channel for rigidity. The other two pieces of angle iron are welded to the running legs of the angles to form a slotted track. A ready-made version can be obtained from a 10-foot piece of square steel door

track. Two bolts with rounded heads are screwed into the rocket body (they must not go into the propellant chamber). When the rocket is placed on the launcher it hangs from these bolts inserted in the track as shown.

The launcher base (Fig. 715) may be made from an 18-inch square of  $\frac{1}{4}$ -inch steel plate. Drill holes in each corner to receive the steel

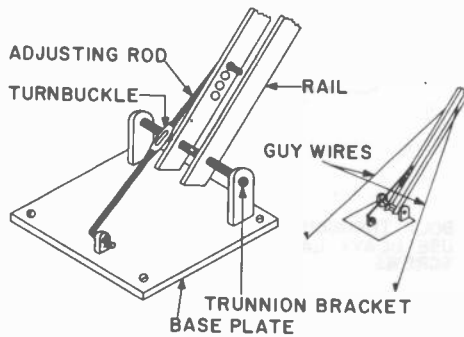


Fig. 715. Launcher base.

hold-down stakes. A trunnion bracket is welded to the plate and the rein is fastened to the bracket by means of a bolt. The elevation angle can be adjusted by setting the adjusting rod in a suitable hole and making fine adjustments with the turnbuckle. When the launching rail is properly positioned in azimuth and elevation, the steel guy wires are securely fastened to maintain the launcher in the correct position during the firing.

Generally the launcher is oriented in azimuth by means of a compass and the elevation angle determined by means of a plumb bob and a protractor. Remember, you do not want an exact vertical shot. An elevation angle of about  $85^\circ$  is best for high altitude attempts and an angle of about  $50^\circ$  is best when you are interested in obtaining maximum range or distance.

### Static testing of the rocket

For the static test we clamp the rocket engine into a fixture so that it cannot go any place. Then we fire the rocket engine to test whether it will function properly. This is a good idea when trying out a new design. Everything can be tested, the firing panel, the igniter and the rocket engine. The same care must be used as in an actual firing, and unless it is absolutely certain that there has been no weakening of or



damage to the rocket engine case because of this firing, it should not be reloaded and fired again.

Two static-test stand designs are given in Fig. 716. In the first

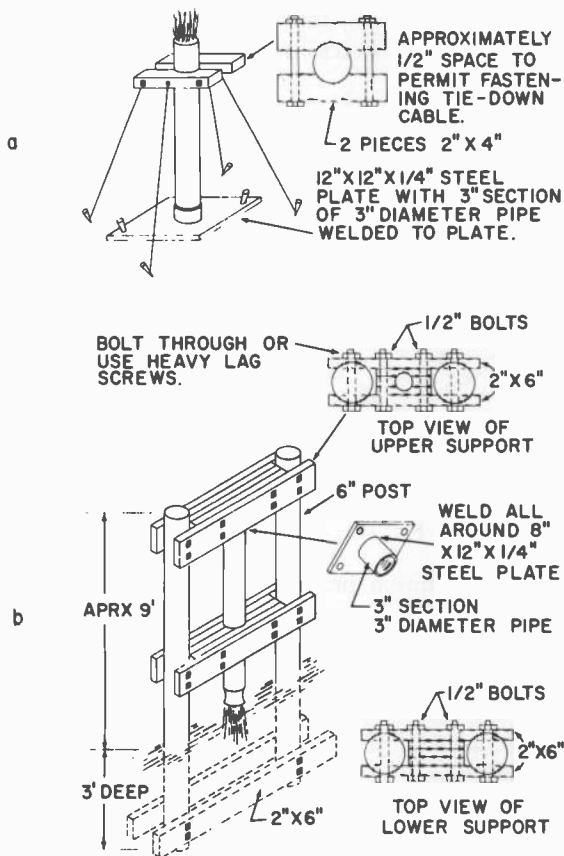


Fig. 716. Static test stands (a and b).

design, the rocket nozzle is pointed up so that the rocket pushes against the base plate resting on the ground. Fig. 716-b shows how the stand might be constructed to hold the rocket while it exerts an upward thrust of 800 to 1,000 pounds. Take care to make this stand strong and rigid.

Remember, learn all you can about theory and practice. If you form a club you can share the expense and be more likely to obtain help from military and civilian rocket experts. Then you can be safely on your way to a new and exciting career in the Space Age.

# robots... facts and fancy

## chapter 8

Perhaps the most fascinating part of radio and electronic control is that pertaining to robots. Robots — the mechanical men of science fiction and reality, human-like in appearance, with strength beyond imagination, whose electronic brains are magic marvels of wizardry; they would do our bidding constantly and tirelessly, performing all those innumerable routine, delicate and difficult tasks we dread so much.

### **The robot age**

It has been said that the years 1920-1930 could have been called the Robot Age ("The Robots Are With Us," Arco Press). In 1932 it was reported that a man by the name of Schaffer designed and constructed a robot which could hammer nails, clean windows, forge iron, saw tree trunks and pile up boards. As it turned out, so the report goes, something went wrong with this robot one day. It suddenly picked up a large piece of metal and demolished its master's workshop as well as its master. This robot was said to have been operated by radio signals and had compressed air actuators. Who knows? Could it have received an interfering signal or was that signal purposely sent?

It was also in the 1930's that the Brainard robot was created. It is interesting to note that this machine was built by a boy just 14 years of age.

Figs. 801 and 802 show Westinghouse's Elektro and Sparko. Elektro can walk, talk, smoke, sing and play the piano. He can identify red and green colors, bow and turn his head 45° in either direction. His

companion, Sparko, weighing 85 pounds and having within his metal skin two electric motors, can walk, sit up, bark and wag his tail.

Here is a robot which responds to spoken commands. A microphone



*Fig. 801-a. A pair of robots.*

picks up the sound, converting it into electrical impulses which operate the relays in his 75-pound brain. The words, of course, must be the correct ones, in a correct sequence, and properly spaced.

### **Televox and Garco**

Then there was the Swiss robot, Televox, which operated through photoelectric cells and which in 1946 crushed its maker as he was

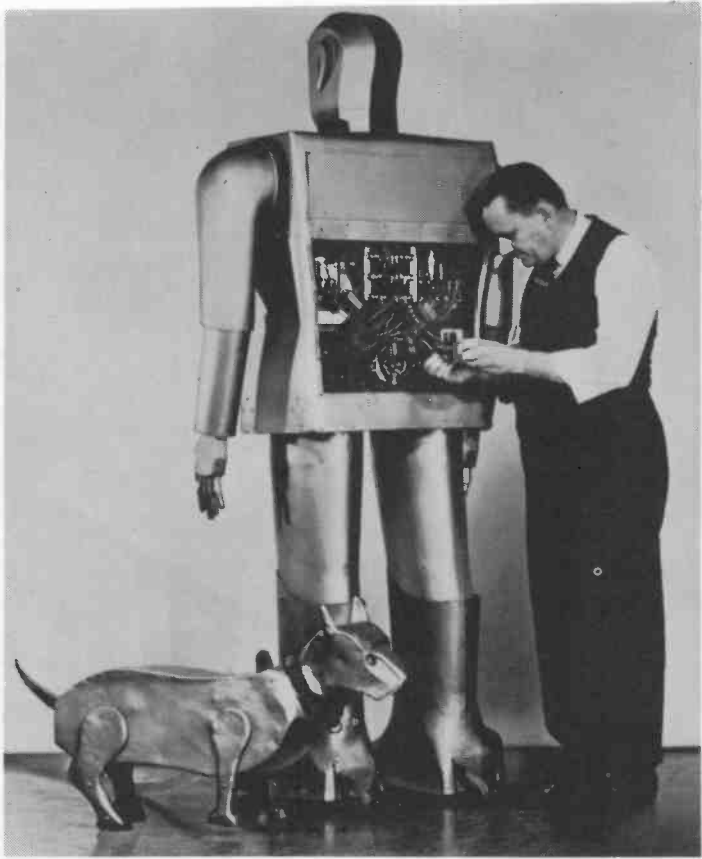


Fig. 801-b. *The robot dog is called Sparko. Elektro is his robot master.*  
[Westinghouse]

attempting to make an adjustment on it. (So much for the historical report.)

In more recent years there have been other, perhaps even more spectacular, robots. There is the report of Garco (*Popular Science*, 1953) who was constructed by an aircraft engineer. This robot was capable of sawing, hammering, drilling, mixing chemicals, picking up papers, stacking boxes, soldering. He could also roll his eyes and play chess. His joints were operated by Wheatstone bridge balances and each arm had five motors; three for torque at ball joints in shoulder and elbow and the others to operate rods which, like tendons, gave a linear push and pull.

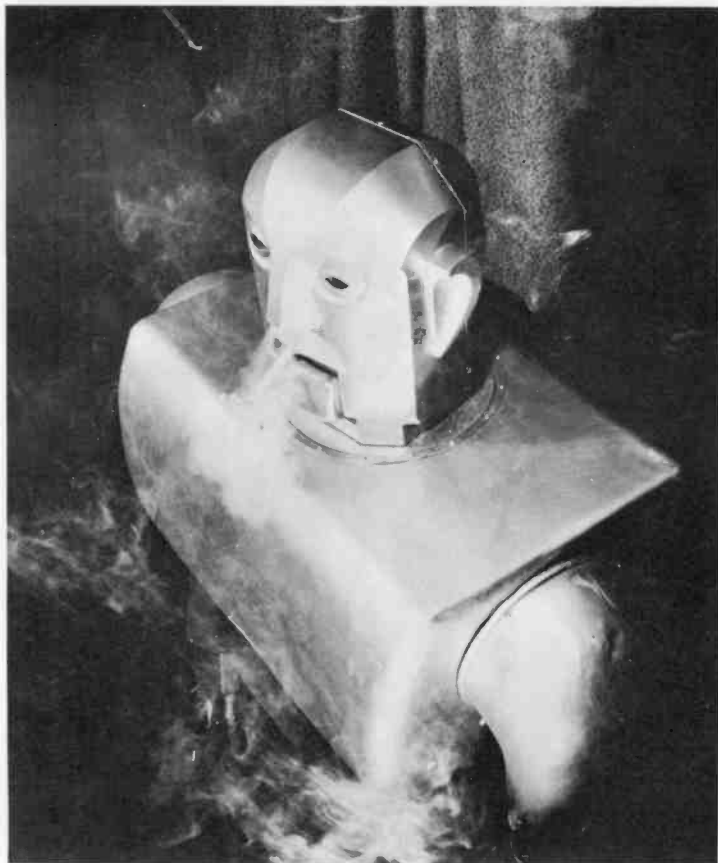


Fig. 802. *Elektro takes a few minutes out for a smoke.* [Westinghouse]

### **Mobots**

And finally, under man-type robots, is the report (1960) of the Hughes Aircraft Company's Mobots. These were developed to perform serious tasks in very unusual environments such as high radiation areas. It is in the Mobots that we find an application of television eyes as well as the use of arms and hands. Mobots operate by means of electrical impulses sent to them through cables and can operate by means of these same signals transmitted over radio waves.

### **Relay Moe**

There have, of course, been many other types of robots constructed which, although they do not have human form, do possess a kind of

intelligence. One of these was the game-playing robot, Relay Moe, reported in *Radio Electronics Magazine* in December 1956, and woe to the opponent who would challenge this electronic marvel.

### Robot tractor

There was the robot tractor (*Electronic News*, 1959) which was tested in England. This device, operating from signals received from a cable buried underground, was expected to plow, cultivate and seed farm lands entirely automatically. In essence, this robot was similar to robot automobiles being tested in the United States.

The concept of control of the robot tractor, or automobile is interesting. A cable, buried a few inches below the surface of the earth, is energized with a low-voltage, high-current tone between 60 and

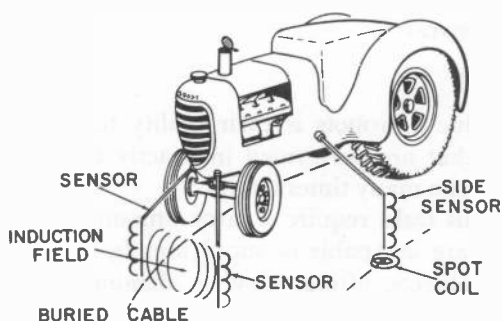


Fig. 803. *Robot tractor plows field without attention.*

1,000 cycles per second. The vehicle has two coil-type (inductive) sensors so positioned that when the vehicle is directly over the cable, the induction field encountered is of equal strength for the two coils. For a simplified system each coil operates a relay, one for steering left, one for steering right. As long as the vehicle is exactly centered over the cable, both relays receive the same magnitude of signal. In another method perhaps the two signals would balance out in a bridge circuit and there would be no steering signals. Let the vehicle get off center, though, and the bridge signals are unbalanced so that one relay will operate to steer in one direction that re-centers the sensors.

Such operations as starting, stopping, applying brakes, and actuating the hydraulic lift are signaled through a second cable placed alongside the steering cable. This one has its own coils set at desig-

nated points along the route. Another sensor out to one side of the moving vehicle passes over these spot coils. Should it pick up a signal, circuits to initiate various other operations can be energized. Fig. 803 illustrates this idea.

The deadliest of robots, the Homing Guided Missile, has but one mission in life and that is to seek out its prey, intercept and destroy it. Once launched, it is on its own, responding to its own sensors. Unaided and unassisted by external control systems, it accomplishes its mission.

And so, with the Space Age upon us, with satellites orbiting the earth and the sun (and soon the moon and other planets), with man himself about to take that step across space, following the robots sent ahead to test the eternal void between worlds, what better way to make our hobbies of radio and remote control keep step than to build a robot or two ourselves?

### **Why have robots?**

The greatest value of robots is their ability to take over routine, monotonous tasks that are performed in exactly the same way every time and must be done many times a day.

Some monotonous tasks require a large amount of physical power which we humans are incapable of supplying. In this category would be the moving of objects, lifting, hauling, digging, etc. A robot can also do precision work that requires exact duplication of an object over and over again tirelessly. There would be no variation in performance as the hours of operation pile up. Some jobs require a day-and-night effort and must go on regardless of weather, time, etc. The robot would not be affected by these conditions and would continue tirelessly until the job is finished, whether it takes a day, week or a month.

Most important would be those tasks which must be performed in unusual environments like extreme heat or cold, in extreme wetness (as on the ocean floor), or in a vacuum as in space. There are radiation hazards, poisonous atmospheres, and other conditions affecting human life.

### **Types of robots**

The robot is actually a unique type of machine which can be categorized according to ability and intelligence.

The programmed robot is not very smart. It can do certain things but only what we have programmed or built into it. A good example is the washing machine. This machine robot will wash clothes exactly

in the same way every time. It washes, rinses, dries and stops. You can put fairly clean or extremely dirty clothes into it and it will wash both in just the same manner. It does its job in an orderly, methodical manner.

A second category is the receptive type robot. This one will respond to commands as to how to do the job. However, like the first, it is still quite stupid, not having a mind of its own. We have to watch it constantly and guide it in all its operations.

The response to environment is a third type. This robot performs certain actions depending upon what conditions it runs into. For example, suppose we wanted to make a robot cat or dog. Primarily we might want it to scoot around the room steering itself and creating general pandemonium until we physically turn it off.

The designing of such a robot (Fig. 804) would not be difficult

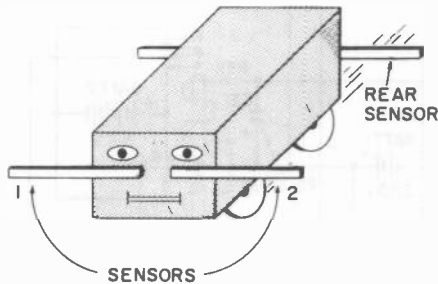


Fig. 804. *Response to environment robot.*

since the only requirement is that it must steer itself. If we provide it with a drive motor and wheels and start it out on a straight line (the environment for it is the living room), it will run into the wall, furniture or people.

It must have sensors or transducers — devices to tell it when it has hit something to make it do something, like back up, turn and start out in a new direction. Of course we must consider how far we want it to back up — it might back into something else.

Let's put this idea into circuitry (Fig. 805). Assume that we have a little car-type object. The body or cover, a dog, a cat or gremlin, can be made up later to suit our fancy. It must have a drive motor and a steering motor. The steering motor must be capable of automatically neutralizing itself so it will normally steer straight ahead.

It must have two front (or forward) sensors (1 and 2) as it is necessary for the robot to know whether to turn right or left when



it hits an object. When the robot strikes an object, sensor 1 (a wire) closes the circuit between Battery 1 and the two contacts X and Y. When Y is closed it energizes relay RY1 so that the polarity of Battery 2 to the drive motor is reversed. This makes the robot back up. At the same time contact X is closed and this causes RY3 to energize, turning the front wheels in such a direction that the robot backs out and away from the object in front of it. Large value capacitors are used across the relay coils. These are necessary to keep the robot moving and steering when its sensor breaks contact with the object it has hit. After a short time, determined by the sizes of capacitors C1, C2, and C3, all relays de-energize and the robot tries to go straight again.

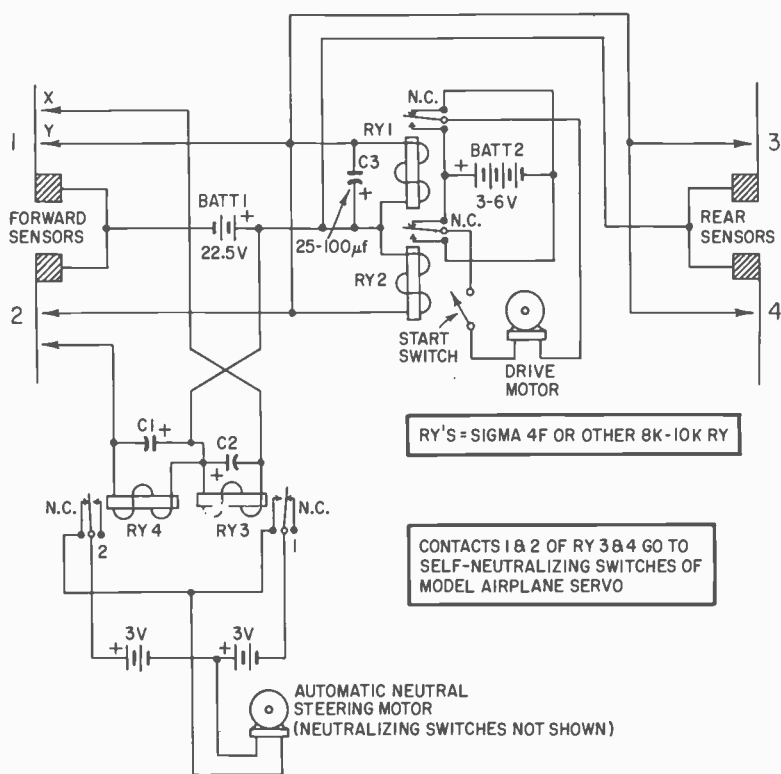


Fig. 805. Circuit of environment responsive robot.

The rear sensors (3 and 4) are provided in case the robot gets into a corner and in reversing backs into an object or wall. Note that

the rear sensors put a short circuit across the reversing relays (RY1 and RY2) so that the instant they close their contacts, the capacitor (C3) is discharged and the reversing relays must de-energize and the robot goes forward again.

One could add to the robot's effect on people by providing it with lights for eyes which would glow when in motion and, with a little imagination, one could cause it to move its head, etc.

So much for the fun part. How can this robot be put to use? Note that this kind of robot, in time, would cover every part of the room we released it in. Suppose we constructed it around a vacuum cleaner and redesigned the sensors so that when it hit a far wall they would cause the robot to turn slightly and then continue in reverse until it hit the near wall. This would be one sure way to interest the feminine members of the household in robots — build them a robot vacuum cleaner.

The thinking robot is in the highest intelligence category. Let us examine the human senses to see how a robot could be equipped to be as nearly human as possible.

A human has eyes. With these he can determine distance, sizes of objects, number of objects, color, type of object, direction and motion. A human has ears. With these he can sense the direction from which a sound comes. By comparison with his memory (and in relation to other senses) he can determine distance, motion and identify what is making the sound.

A human has a sense of touch. With the fingers, as well as other body surfaces, he can determine smoothness, roughness, heat, cold, size, shape, motion (if the object touched moves), nearness of objects to his body.

A human has a smell sensor. With this he can determine location (remember the popcorn stand?) and identification — food, perfume, etc.

And a human has a brain.

Eyes for a robot might be provided by a pulsed ultrasonic system (like sonar) which, acting like radar, would provide intelligence concerning objects and motion. It could not provide information concerning color. Imagine a robot moving along a level path which abruptly terminates in steps. The pulsed echo return from its sensors would indicate when the walk became steps, the height of each step and how many.

Ears could be duplicated by microphones and be made to function much as the human ears do. By triangulation on the sounds, just the

head or the whole robot could be made to turn until it faced the source of a sound exactly.

Duplicating the sense of touch is more difficult. One possible device might use capacitance effects. The sensor would be connected to an oscillator and the frequency of the oscillator would change as the sensor (hand) came close to objects. Actual feel is more difficult. This might be accomplished through additional sensors and feedback circuits in the hands and fingers which would tell the brain when they had grasped something, how much pressure was being exerted, whether the object was remaining rigid or was deforming under pressure. Heat, cold, etc. could be detected by sensitive transducers

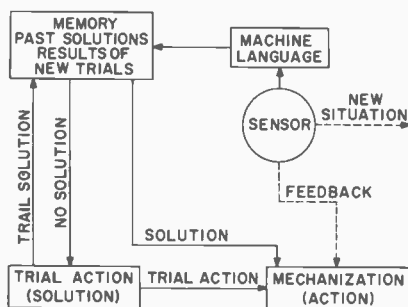


Fig. 806. Thinking robot brain. 1. Sensor determines situation. 2. Machine language block converts information to pulses. 3. Memory records situation, hunts for solution. 4. If solution is present, memory sends command to Mechanization. 5. If no solution, Memory routes situation to Trial Action. 6. Trial Action unit determines an action based on "best guess". 7. Trial Action recorded by Memory. If successful, no further trials. If not successful, Trial Action unit tries another solution. Memories may be magnetic drums, tapes, magnetic cores, etc.

made as an integral part of the hand. Smoothness and roughness of an object or surface could be measured by vibration-type detectors which would be activated to a lesser or greater degree as the fingers would pass over the surface.

For the smell sensor, there are machines which give an output according to odors and which were developed by the Chemical Corps for gas detection.

Thus, it seems within the range of feasibility to give the thinking robot many of the senses that humans have. The degree to which

this can be accomplished would depend on the degree of instrumentation possible within the robot.

### The robot brain

The basic brain of the thinking robot is illustrated in Fig. 806. Note that it implies sensors of various types, a language conversion unit which would change the sensor information (pulses, tones, etc.) into a language or signals that the brain proper could understand. The memory unit would store all the past experiences, all the possible solutions to all possible combinations of sensor signals. The trial action part of the brain will help the robot think out unusual or extraordinary situations. Finally, there is the mechanization unit which causes the robot to speak, move its arms, turn its head, or whatever is appropriate. There must be external as well as internal feedback for the mechanization system.

For an example as to how the brain would function, let us assume that our robot is moving down the walk. It is able to detect the edges of the walk, walls, etc. As these signals appear in the sensor output they are converted into impulses which are passed on to the memory unit. Assume that this memory unit is a magnetic drum (Fig. 807)

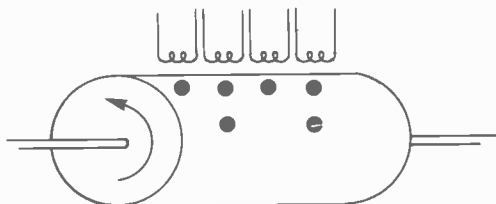


Fig. 807. Memory unit is a magnetic drum. Dots indicate stored information picked up by coils as drum rotates.

which records these impulses according to which sensor the signals originate from or that there is a magnetic drum for each sensor.

Imagine that suddenly someone casts a sack over the robot so it can no longer see where it is going. The immediate loss of eye information causes the eye-sensor memory drum to spin, searching for a condition that matches this loss of signal condition. If there is a comparison in the memory, the circuits comparing the input signals from the sensor to the signals from the memory cause another signal which

would be sent to the mechanization unit along the solution-action line. In this case, the solution action might be one or several commands or signals in sequence to cause these to happen: Stop! Raise arm, brush hand across face.

### Finding a solution

If, however, there is no repeatable solution in the memory, the memory sends the problem down to the trial action unit. This unit will select a solution on the basis of how well the memory and input signals match. If they are very close, then the trial action unit might sign a stop motion command and then perhaps a turn. As the robot turns, signals again whip through the memory and comparison circuits go down to the trial action and if this was a solution, there would again be signals from the eye sensors. If this is not a solution and there is still no signal from the eye sensors, the trial action unit signals this information back to the memory for storage. The memory must store not only successful solutions but also solutions which were not effective.

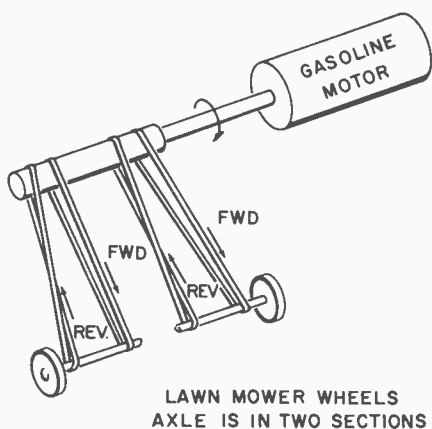


Fig. 808. Obtaining forward and reverse motion from a unidirectional motor.

Now that the trial action unit has determined that the problem is not a condition of direction, it might effect a test of circuit operation, an automatic internal check, so to speak, of the operation of the sensors, holding the robot motionless while it does so. Finding these all right, it causes another series of tests and test actions until finally, by

trial and error, it arrives at the correct solution of having the robot rub its hand upward over its face to remove the cover.

The human mind works in much the same way. We base our actions on experience and we store our successes and failures in our memory units. We also effect trial solutions in everything we do and learn, providing our memory with information, as a result. Machines can do the same thing by using computers as brains. This would be the thinking robot, a machine which could analyze situations and have near-human sensors, memory and trial-action reasoning elements.

**Building robots**

The receptive robot most nearly fits into our command-control category. Let us consider building a robot lawn mower. To evaluate the job it is to do: It must be able to start, stop, go forward and

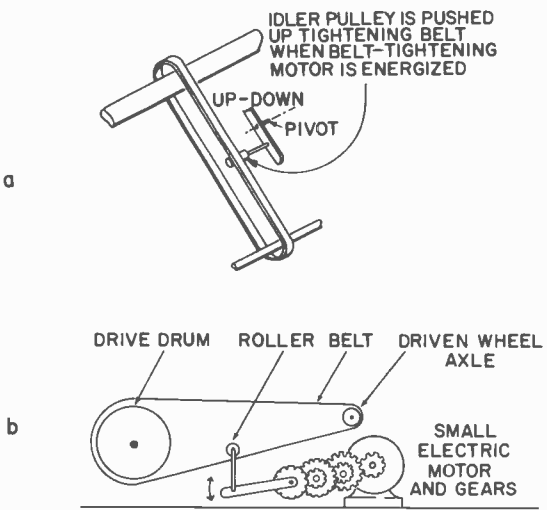


Fig. 809. Belt tightening roller [a] and side view of belt tightener [b].

reverse, turn left and turn right. Six commands will be needed; this might mean six control channels.

Usually we do not have to send any commands simultaneously, except possibly the forward (or reverse) movement and the steering. Here we could start the machine going forward (or reverse) and then steer it. To refine it, we might want to do both at the same time.

How do we accomplish steering? The mower will most likely be driven by a small gasoline engine which will run all the time; there-

fore we would want our control system to disengage clutches to one wheel or the other so that our turning would be accomplished in the same manner as one steers a tractor.

We cannot actually reverse the drive engine, so that our reversing action must be accomplished by engaging gears or clutches which will cause the mower to reverse even though the drive motor always turns in the same direction. This then would also indicate that starting and stopping would involve disengaging the clutches completely.

Fig. 808 shows a basic method of obtaining forward and reverse rotation of the drive wheels, individually, from a gasoline engine which runs in one direction. The concept is simple, consisting only of having two belt drives to each wheel. One belt is not twisted, the other has one twist in it. This twist causes the reverse rotation. As far as obtaining the drive is concerned, small rollers on each belt (Fig. 809)

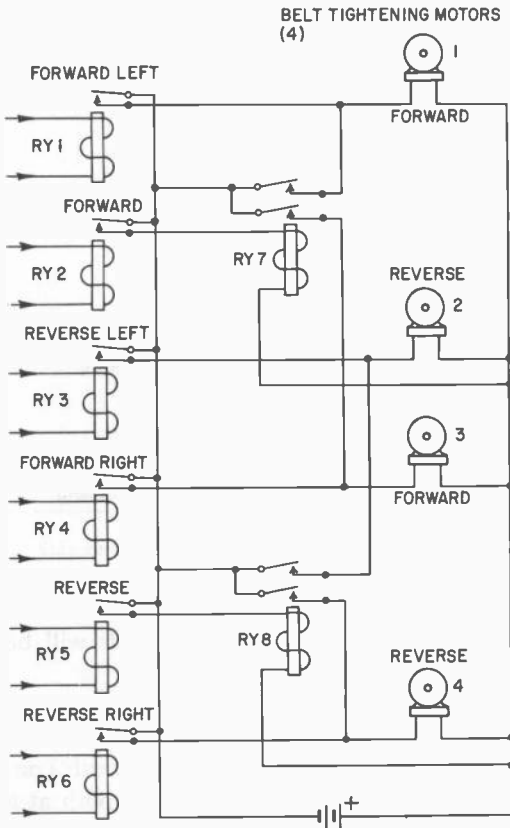


Fig. 810. Robot lawn-mower wiring diagram.

which would tighten that belt when the command is given, would do the job. Four such rollers would be required and in the off position all would be loose. The relay wiring to the small electric motor which would tighten the belts should be wired according to Fig. 810 so

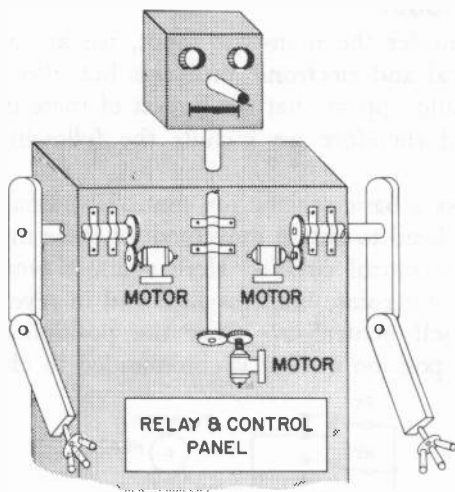


Fig. 811. Man-type robot arm and head drive.

that when the first command is given, both forward-drive belts are tightened. When the command for steering left is sent, only one forward belt is engaged and for right steering the other forward belt is engaged. To steer while moving in reverse, each of the reverse belts must be engaged separately.

In the schematic (Fig. 810) eight relays and four small electric motors are shown which, when energized, cause the individual belts to tighten. When RY1 is energized alone, motor 1 pulls its pulley until the belt is tight. It then stops its rotation because it has opened its own limit switch. When the signal stops and RY1 opens, motor 1 will loosen its belt due to its own self-neutralizing action. Note that these little electric motors are nothing more than self-neutralizing model airplane servo motors. Thus RY1, when energized, would cause the mower to go forward but turn left.

To turn right, RY4 would be energized and exactly the same actions would take place for motor 3 and the mower would turn right. When RY2 is energized, it in turn energizes RY7 which energizes both motors 1 and 3, tightening both forward-drive belts. Thus the mower would go straight forward.



Energizing RY5 causes both reverse-drive belts to be tightened. Reverse steering would be similar to forward steering.

### The man-type robot

When we consider the man-type robot, we are again faced with not only electrical and electronic problems but also with mechanical problems. It would appear that the largest of these is the mechanical construction and therefore we include the following for a starting point.

Fig. 811 shows a basic scheme for connecting small electric motors to the arms and head to obtain movement of these members. Fig. 812 shows the motor-control circuits. Here again it would be necessary to make each motor rotate both forward and in reverse. These drives should not be self neutralizing since the positioned member must often remain in position until it is commanded to change. The three

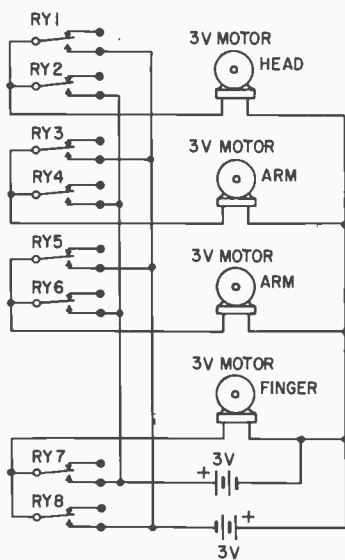


Fig. 812. Method of connecting motors to relays. Relays are activated by reed decoders.

motors would then require six control channels. Each motor would have to have limit switches to prevent over-travel of the primary members.

We should be able to control the elbow joint. This, too, must contain a small electric motor that will cause the forearm to raise or lower (Fig. 813). Since we have one motor for each forearm and

each motor must be capable of being driven in either forward or reverse direction (up or down) this requires at least four more channels.

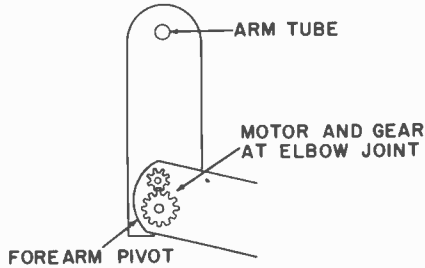


Fig. 813. Elbow joint movement is obtained by motors and gears. Wires from the elbow, wrist and hand go up through the arm and into the body through the arm tube.

Now we come to the wrist and finger. Only one finger is shown but this can be expanded to more fingers if desired. As shown in Fig. 814, the wrist-drive motor is limited to 45° rotation in either direction,

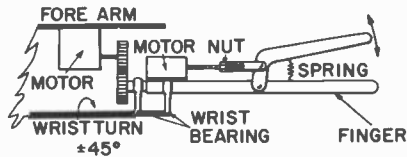


Fig. 814. Wrist and finger detail.

which is enough for the wrist motion. Another motor is connected through a linkage to the finger. When this motor runs in one direction the finger is opened, pulling against the spring pressure. When the motor runs in the opposite direction, its lead screw nut moves away letting the finger close again due to the spring pressure. Two more bidirectional motors are required for each hand. This means eight more control channels are needed.

Finally, there is the motion of the robot. Fig. 815 shows how the leg might be pivoted in the body and the little drive motors placed in the shoe which is hinged to the leg so that it can always remain parallel to the floor. The walking process might be accomplished by energizing a little device inside the robot which would cause one leg drive motor to run first, then the other, automatically (Fig. 816).

Each would operate for just the correct interval of time to give good forward motion. Note that the pivot must be above the center of gravity of the body, otherwise some kind of body stabilization, such as a gyroscope, would be needed to keep it erect. One might consider a lady robot as a simpler approach for then, because of a long

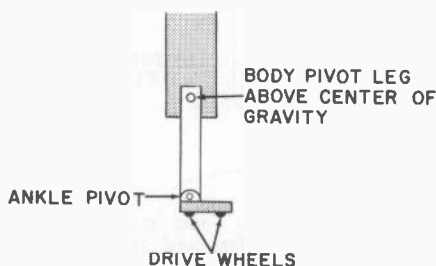


Fig. 815. *Robot moves by drive motor and wheels in "foot."*

dress down to the floor or near it, it would not need to have legs as such.

It is a real challenge to the experimenter and builder to construct such a robot or mechanical man. Not only would he be getting a real education in the concepts of automation and control but he would also have the fun as well as the satisfaction of being able to make it operate. To steer a robot and make it pick up objects and do useful things constitutes a far greater challenge in control systems than do the usual boats, cars and airplanes.

We have suggested basic construction methods and indicated the minimum number of control functions required. Undoubtedly someone will come up with ideas of his own and devise a control system which might be a great deal simpler and require far less channels than we have indicated. It's a challenge — give it some thought!

### **Robots which respond to spoken commands**

When we consider how to make a robot respond to the spoken word we can think back to a model airplane control system which would cause the elevator to move up at the word "up" and down at the word "down" and to neutral at the word "neutral." This is really a system which produces the illusion of having the airplane respond to the spoken word. Actually (using a microphone input to an audio amplifier which, in turn, activates a relay), the system works the model control system much in the same manner that present radio control systems activate a relay and escapement when a tone is received.

All three operations are performed in sequence and all that is required to activate the system is a sound — any sound that can be picked up by the microphone. If we chose to say the word “up”,

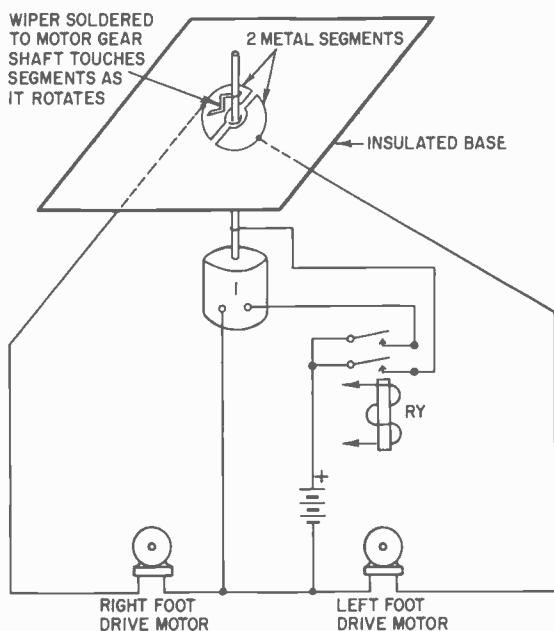


Fig. 816. Automatic walking programmer. When the relay is energized, motor 1 runs, turning the wiper [through a gear train]. As the wiper touches metal segments, each “foot” motor is caused to run in sequence and for the same length of time. The relay is energized when the command to walk is transmitted. This command is one reed tone.

which was done in this case, the sound causes, the first operation — up elevator. We always have to follow this with the word “down” since that word would be the next operation performed; then, of course, we next have to follow this with the command for neutral. This is a system that might be used for parlor tricks with friends, cautioning them first that absolute quiet must be maintained while the robot is operating. Otherwise the robot will not be receptive to the spoken word. We leave it to your imagination to visualize any other exploitation of this idea.

Actually, there is a large amount of scientific research being carried on to characterize human speech sounds and to determine different characteristics which identify them and which could be used to effect control operations. One useful end product of this idea

would be a robot stenographer which would consist essentially of a typewriter connected to a decoding machine. The device would type out the page in response to human-voice dictation.

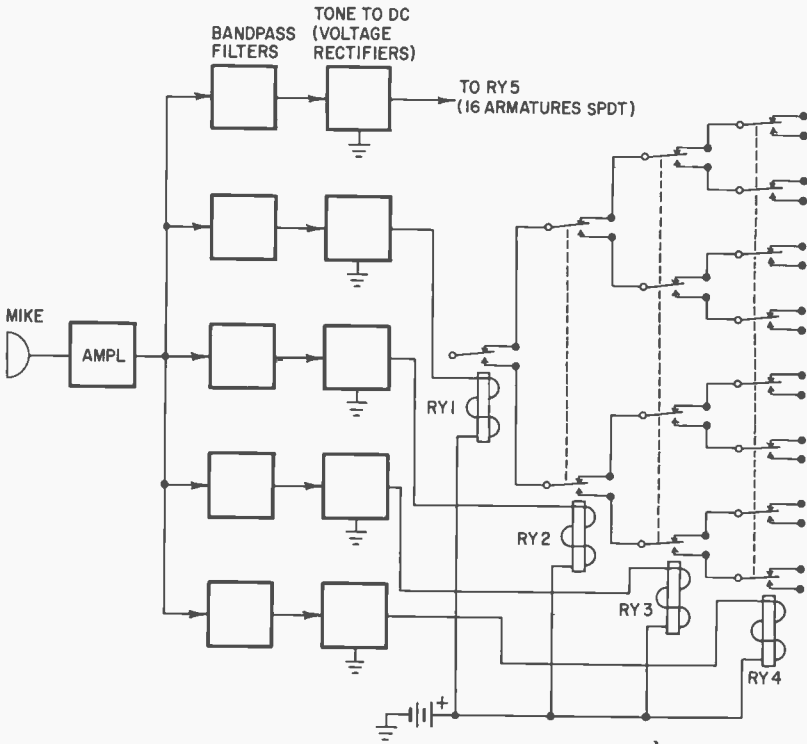


Fig. 817. Details of voice-control system. Five filters give  $2^5$  [32] functions.

Because human words (syllables, etc.) do have different characteristics it is possible to take words which are predominant in sound differences and feed them into a selective decoder and then to a small computer, causing operations such as those performed by Elektro. Combinations of high-pass, low-pass and band-pass filters selecting the amplitude and magnitude of the various tones in the word structure can result in a particular mechanical operation. For example, the word "this" has a sibilant sound which is somewhat prolonged. The word "stop" is short without sibilance. So the tonal characteristics (frequencies) and the way they are combined to form word sounds, then length of the sound, etc., all contribute to the method by which

we, as humans, recognize and interpret the human vocabulary. As machine intelligence increases there is no reason why it cannot be given this same ability in a mechanical sense.

Consider the feasibility of multisyllable words where each syllable, when spoken carefully, results in the same kind of coded command as a pulse command. Cig-ar-ette, for example, has three syllables which can be spoken within a precise time interval. Each syllable has certain frequency characteristics which make it different from another three-syllable word, such as re-treat-ing. Two-syllable words differ in the same way; for example, play-ing and be-gin. So when we recognize that for syllables or words spoken closely together each syllable or word represents different frequencies or groups of frequencies, one can readily see how a multitude of specific commands could be created.

Fig. 817 shows how the basic electronics of such a system might be laid out. The microphone picks up the sounds, the band-pass filters separate these into their various frequencies from which the rectifiers produce dc currents which cause the control relays to operate in such combinations that the desired movements are produced.

## **Robot brains**

Earlier we discussed the general operation of the thinking robot's brain and gained some idea as to how it might operate. The brain of a robot is perhaps the least understood of all its parts. Is a robot brain a computer, and if so, just how does it operate to cause the robot to perform all the various things we want it to? Sometimes, to answer these questions we get books explaining the operation of computers and then try to apply our study to an understanding of the operation of a robot brain. Sometimes we just get more confused.

The brain of a robot may be thought of as a computer but in another sense we may find it is not a computer at all. If we analyze just what this part of a robot does, we will find that a very large function performed is simply comparing the information, received from various sensors, to other information which may come from sensors or a storage unit. This comparison, simply the combining of signals of different polarities or phases, produces a third signal, which, in turn, causes something to happen.

Let us develop this concept further. Suppose the robot has two photoelectric cells for its eyes and the 'brain section' is a circuit which will compare the inputs from each photocell. It is not difficult to imagine if one cell receives a flash of light while the other does not, that the resulting signal (which might come from a bridge circuit)

would have, say, a negative polarity. This type of signal would be passed on to an amplifier which makes a little motor run. The motor would operate, possibly counterclockwise. When this happens, the robot would turn to the left quickly. We say quickly, because the signal would be large as it is the full output of one photocell.

Following the same line of reasoning, if there were a flash of light which illuminated both 'eyes' (photocells) but illuminated one a little more than the other, the comparison circuit would produce a *difference* signal whose polarity would correspond to the signal from the cell with the larger illumination. The result would be a weaker signal to the electric motor—because now the output of one cell subtracts from the other. Thus the robot would turn more slowly. Note, however, that it *would* turn until the inputs cancelled.

This idea can be applied to sound, radar-type pulses, light, heat, odors, pressures, or other physical phenomena which can be recognized by electronic or physical sensing devices. This idea of a comparison circuit, then, is one of the fundamental circuits of a robot brain.

### **Programmed action circuit**

Now consider a second type of circuit which is important. This is the 'programmed' action circuit—a type which will make various things happen once it is activated. These actions will be performed in sequence and will continue unless some other signal is received which either changes the 'program' or causes this programmed operation to stop. Such a circuit might be a simple automatic stepping relay which, once started, clicks around contact by contact in accordance with some predetermined stepping time interval. Each of the contacts that it clicks through would cause other circuits to be energized—perhaps just for a moment, perhaps long enough to start subprogramming routines. And, as these other circuits start operating or the subprogramming routine start working, this, in turn, might produce new input signals which would have an effect on the main programming relay. They might cause it to stop, reverse, move faster or slower as the information might demand. You can see that this kind of circuit is responsible for most of the robot's actions. It actually becomes the robot's 'nervous system'.

Let us explore this idea further. Suppose you want a robot arm to move around a table top. This arm is to be equipped with a claw or fingers to grasp small objects, such as small blocks. You want the arm to locate these small blocks anywhere on the table top, identify them, pick them up and put them into a taller box which might also be on the table. Also, you want the arm to locate the tall box and determine

if it is filled with blocks or whether it is empty. You might say that this arm would have to have a brain—a computer—to be able to perform these tasks.

Certainly the first requirement is that the arm must be able to sweep back and forth across the table top. It must also move forward from the back edge to the front edge. We will assume that the arm is to be located at the middle of the table and therefore as it sweeps back and forth, its length must increase as it swings out toward the edge of the table to maintain contact with the table top. With a little thought we can imagine an electronic circuit which will cause a little motor to run back and forth—back and forth—to cause the side movement. We could also imagine a second motor positioned so that it would cause the arm to move forward a few inches after every sideways sweep. We can further imagine a set of contacts, attached to the hand, which are held in the 'open' position by the pressure of the arm on the table. As the arm swings to the right, say, and as the angle from the vertical increases, the hand would tend to rise above the table top. This would cause these contacts to close, and they in turn would cause a third motor to run, lengthening the arm until the pressure of the table top again opened these contacts. Thus we have two 'programs' and a direct command sensing circuit. When no blocks are on the table, the arm will sweep back and forth and move from the back to the front of the table, and will maintain contact with the table top. One more thing here—if the arm goes off the table top, the pressure contacts lengthening the arm will close, this motor would run and the arm grow longer and longer. We must provide 'limit' switches\* on the arm length to stop everything if this happens.

Now we come to object identification. Let us provide the 'claw' with contact switches, one located on each side. As the arm sweeps, if it should come in contact with a block on the table, one of these 'side sensors' would be closed. When this happens the side sensor produces a signal which stops the 'sweeping' program and causes another program to start immediately. This second program would be the running of a small motor which causes the arm to raise, or get shorter. Now, here is a key concept. If the arm raises just a small amount before the side sensor opens its contacts, additional contacts located on the arm, held closed only during a short upward movement, would cause the arm to position over, say two inches, in the direction that the block was located. It would have identified the block because the side contact of the claw opened during a given upward movement of the arm. This, in turn, causes the subroutine

\*See Gernsback Library No. 74—Model Control by Radio



programs to go into effect giving first, the two-inch movement over the block; second, a downward movement back to the table top, sensed by the claw's bottom contact, then a closing of the claw to grasp the block, and once contacts *inside* the claw are closed due to the grasping of the block, still another program is activated making the arm raise, move to a predetermined position over the large box and then releasing the small block.

The identification of the large box would be made because the claw 'side-sensor' would remain closed during a longer upward travel of the robot arm. When this box is identified in this manner, a subprogram would simply make the arm move over a given amount, come back down on the table and continue sweeping and searching for small blocks as before.

This, then, is an idea of the operation of a robot brain where the robot responds to a general command, but it, itself, determines its actions by what it finds on the table and where it finds them.

As you see, we have input sensor commands which in a sense are modifying a programmed operation by causing different predetermined programs to be set into operation. Consider these concepts carefully and you'll be surprised at how lifelike your robot can become, as well as challenging in concept and construction.

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