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APPLICATIONS
of
HIGH FREQUENCY SATURABLE REACTORS

by

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THE RADIO CLUB OF AMERICA

11 West 42nd Street ★ ★ ★ New York City

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APPLICATIONS OF HIGH FREQUENCY SATURABLE REACTORS

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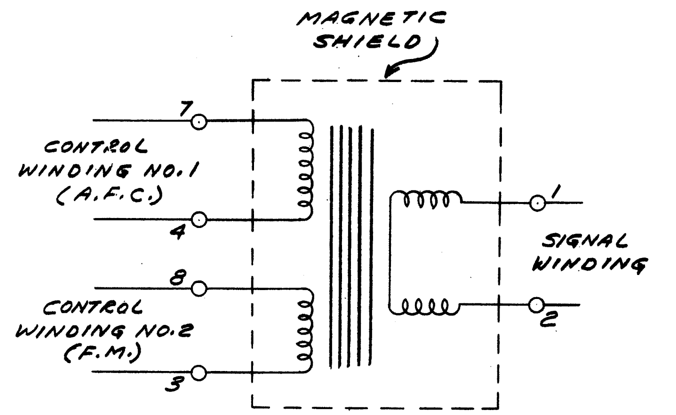
CARL G. SONTHEIMER*

The saturable reactor is a device comprising a magnetic core with a number of windings. Some windings carry alternating current; others, direct or slowly varying current to determine the magnetic state of the core and thus to control the alternating currents in the windings first mentioned. The devices discussed here operate on exactly this same principle, but the frequency range has been extended to beyond 100 megacycles. The Q's have been increased to several hundred in some cases, and other parameters improved so that these modern saturable reactors constitute a new component for the circuit designer. For this reason, they will be referred to as "controllable inductors". Figure 1 shows typical high-frequency controllable inductors. Figure 2 shows a schematic representation of a controllable inductor having one signal winding and two control windings. The signal winding is drawn in two sections shown orthogonal to the control windings to indicate that inductive coupling between the control and signal windings has been cancelled. A magnetic shield surrounds the assembly to prevent stray fields from influencing its behavior. This unit is used in an oscillator tank circuit of which the signal winding forms the inductive component. One of the control windings provides wide band frequency modulation of the oscillator while the other furnishes automatic control of the center frequency.



SCHEMATIC
TYPE 618T2 INCREDUCTOR
CONTROLLABLE INDUCTOR

Figure 2

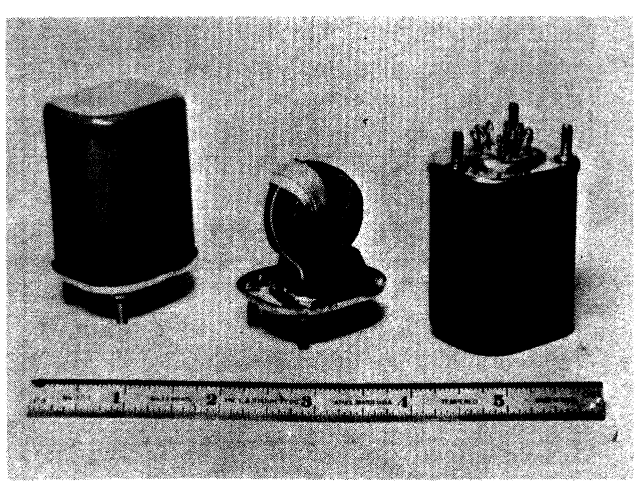


Figure 1A

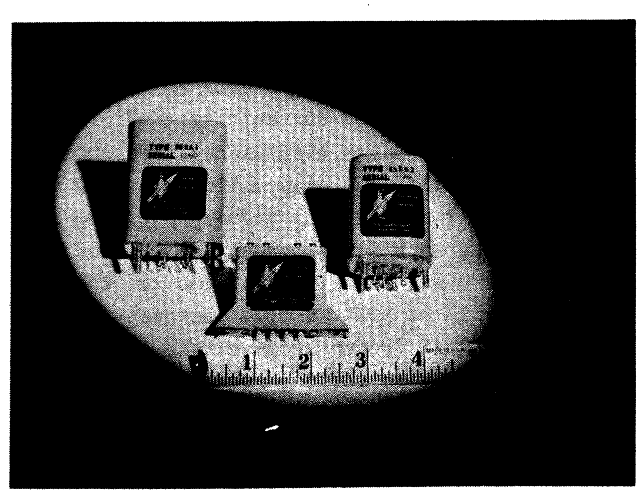


Figure 1B

*CGS Laboratories, Stamford, Conn.

Much of the information needed before using a controllable inductor can be presented on a single chart called a "Q map" shown in Figure 3. Frequency is plotted vertically and inductance of the signal or controlled winding horizontally, both on logarithmic scales. This unit has a maximum signal inductance of about 66 microhenrys in the demagnetized state at zero control current. A second horizontal scale indicates the control current required to reduce the signal inductance to the corresponding value on the inductance scale. At the maximum continuous control current rating of 100 ma, the signal inductance drops to about 0.9 microhenry. On control current peaks exceeding 100 ma, the inductance is further reduced to about 0.6 microhenry. The map itself is obtained by measuring the Q of the signal winding at various combinations of applied frequency and control current and then joining points of equal Q to form constant Q contours.

To illustrate the use of the Q map, assume an application in which the signal applied to the controllable inductor signal winding is always to have a frequency of, for example, 2 mc. A phase modulator might be such an application. At zero control current, the Q will be less than 30. Crossing the Q map along the 2 mc line, we see that when the control current reaches about 4.5 ma, the signal inductance has dropped to about 30 microhenrys and the Q has a value of 30. With further increase in control current to about 12 ma, the Q increases and reaches a peak value between 70 and 86. This corresponds to a signal winding inductance of 5 microhenrys. From here on, an increase in control current causes a decrease in Q. Finally, at about 100 ma, the inductance has reached a value of 0.9 of a microhenry and the Q has fallen to 30.

In another application, such as a square wave modulator, the control current might alternate between two fixed values with signal frequencies varying, for example, between 400 kc and 10 mc. If one of these fixed current values should be 20 ma, corresponding to a signal inductance 2.6 of microhenrys, the Q map shows that at 400 kc, the signal winding Q will be 30. It will increase to almost 86 as the signal frequency is raised to 3 mc; and as the frequency is further increased to 10 mc, the Q will drop back to 30.

In the many applications where the controllable inductor is used as the inductive element of a tuned circuit, it is easily shown that the resonant frequency traverses the Q map at an angle of about 35 degrees as control current is varied. A number of such lines, each corresponding to a different value of tank capacitance, are shown at the right-hand side of the map. One line segment corresponds to a 1,000 mmfd condenser. In this case, the resonant frequency at zero control current is about 620 kc. If this line is extended to cross the entire map, we see that at 100 ma control current, the resonant frequency has risen to over 5 mc,,a frequency range of somewhat more than 8 to 1. The Q of the tank circuit lies between 30 and 50 at 620 kc, reaches a peak of 86 at 3 mc, and falls back to about 60 at 5 mc.

The Q map is very useful to the designer,but certain precautions must be observed. Most controllable inductors have appreciably larger temperature coefficients than typical fixed components. There is generally a value of control current for which the temperature coefficient is substantially zero, with coefficients of opposite sign on either side of this current setting. Signal winding coefficients of one-half of one per cent in inductance per degree are encountered although more typical values are 0.1 to 0.2 per cent. These are sufficient to change the appearance of the Q map considerably over temperature ranges that many types of equipment must endure.

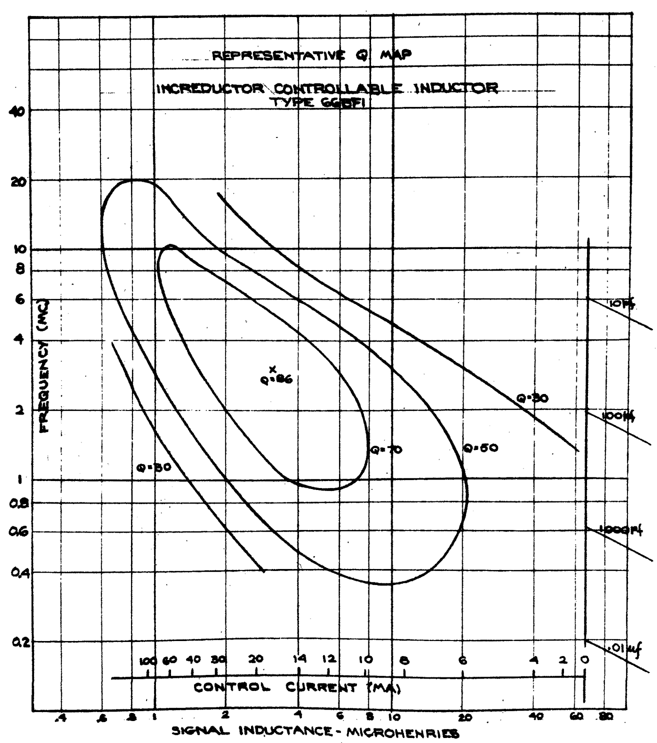


Figure 3

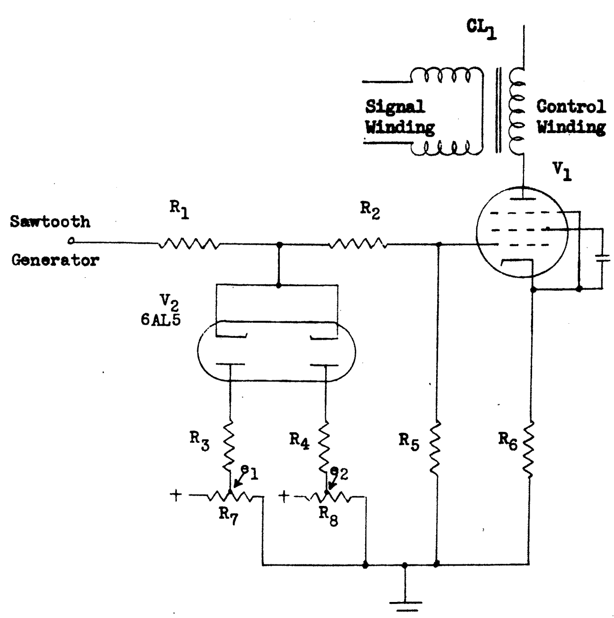
Moreover, controllable inductors, like other magnetic devices, show hysteresis phenomena. If the control current is raised from zero to a given value, one signal inductance is obtained. If the same control current value is arrived at from a higher current setting, a different value of signal inductance will occur. Signal winding Q is not generally affected by hysteresis, and the only effect of hysteresis on the Q map is in the use of the nomograph formed by the two horizontal scales. A common convention, adopted in the Q map on Figure 3 is to show the values of signal inductance which correspond to monotonically increasing control currents.

The unit described by this Q map has an inductance change ratio from zero to full control current of about 80 to 1 and a peak Q of about 86. At frequencies up to 10 mc, inductance change ratios in the hundreds are feasible; and commercially available units have ratios up to 400. Typical units designed for applications between 10 and 50 mc have ratios in the order of 30 to 100. In the 50 to 100 mc range, this drops to between 3 and 6 and above 100 mc, to less than 2 to 1.

Representative peak Q values are in the low hundreds for frequencies up to several mc. They range between 40 and 100 for frequencies up to 50 mc, dropping off to between 10 and 50 at 100 mc and perhaps 5 to 10 at 200 mc. Q may always be increased at the expense of inductance change ratio. The control power required to obtain the full inductance variation of low level units is rarely as high as 1 watt and, for many commercially available inductors, ranges from 0.1 milliwatt to 100 milliwatts. As this Q map shows, the relationship between control current and signal inductance is quite non-linear. The percentage change in inductance per unit control current is greatest for small control current values. This is usually quite undesirable. Appropriate circuitry has been developed to remove this and the other undesirable effects of temperature drift and hysteresis.

Figure 4 shows a method often used to make the signal inductance a reasonably linear function of control current. The values of R3 and R4, as well as the settings of potentiometers R7 and R8, are chosen so as to provide expansion of the input control signal. With a single 6AL5, linearities of 10 per cent or better are generally obtained. Sawtooth control voltage input is usually supplied to the pentode used to generate the control current. Since the control winding is also inductive, operation from a low impedance source would discriminate against high frequency components in the control current. For this reason, pentodes are usually employed.

In some applications, controllable inductors are used as adjustable linear components, as when they are used to replace mechanically variable tuning condensers. An example is the sweep oscillator. Here the controllable inductor makes possible wide frequency range with high output volt- free from spurious frequencies. Up to several megacycles, an inductance resistance analog of the well-known Wien Bridge Oscillator may be used. This was described by Pressman and Blewett in the January 1951 issue of the Proceedings of the IRE. Frequency ranges in excess of 100 to 1 are feasible, such as 15 kc to 2 mc. In LC oscillators, starting at frequencies up to several mc, ranges of 10 to 1 may be obtained, such as 3 to 30 mc in a single band. Starting at 15 to 25 mc, ranges of 3 or 4 to 1 are possible. Above 100 mc, the range drops to the order of 10 to 30 per cent.



R_1, R_2, R_3, R_4 order of 100 K to 1 Meg.

R_3; R_4 determine slope of current vs. voltage curve.

e_1, e_2 set the values of voltage at which the slope changes.

CL_1 - INCREDUCTOR* controllable inductor

* Trade Mark

Figure 4

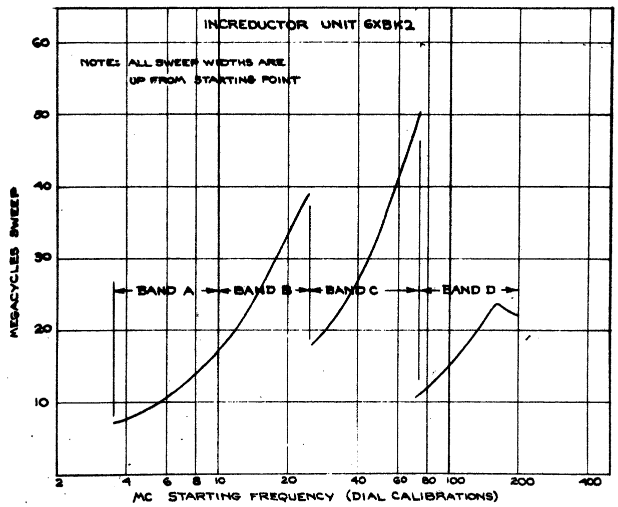


Figure 5

A specific example is provided by a recently announced sweep generator kit which provides coverage from 4 to 200 mc. A controllable inductor with four signal windings is used in a Colpitts circuit, and the sweep obtained is shown in Figure 5.

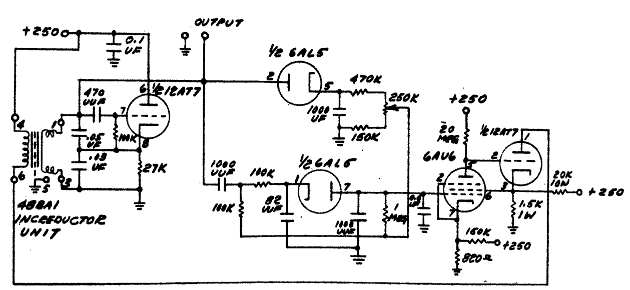
There are four bands. This figure shows the sweep width obtained at each starting frequency. A variable condenser is used to set the starting frequency as desired within each band. At 4 mc, a sweep of over 6 mc, that is from 4 to 10 mc, is available. At the upper end of the first band, the sweep range is 10 to 25 mc. The second band covers starting frequencies from 10 to 25 mc, and the corresponding sweep widths vary from about 17 to over 35 mc. In the third band, the corresponding sweep widths are 17 at the low end and 50 at the high end, as may be seen from Figure 5, which shows that at a starting frequency of 75 mc, the sweep will cover the range 75 to 125 mc. On the high band, with starting frequencies ranging from 75 to 200 mc, the available sweep width varies between 10 and slightly more than 20 mc. The oscillator is amplitude controlled and delivers 0.1 volt to a 50-ohm load.

In sweep and other types of oscillators, automatic frequency control of the center frequency is sometimes desired. The controllable inductor provides AFC action with greater pull-in range than generally obtainable with other means. Adequate loop gain is often obtained with the control winding fed directly from the discriminator cathodes. Specially designed units with split control windings are used for this purpose.

The large inductance change ratio and small power requirements of the controllable inductor suggests its application to telemetering. Unless errors of several per cent can be tolerated, temperature drift and hysteresis effects must be overcome.

Figure 6, which shows the circuit of a remotely controlled oscillator covering the range 30 to 100 kc, illustrates the circuitry developed for such purposes. Half of a double triode is used for the oscillator. Part of the output is fed to a discriminator circuit consisting of a 6AL5 operated in the following manner. One of the diodes is driven through an integrating circuit which provides a response inversely proportional to frequency. The other diode produces a rectified output of opposite polarity across a potentiometer and is fed directly from the oscillator. The two rectified voltages are placed in series and the output taken from the tap of the potentiometer. Zero output may be obtained for any frequency within range of the oscillator by adjusting the potentiometer. The discriminator output is fed to a d-c amplifier consisting of a pentode direct-coupled to the other section of the double triode. This closed control loop forces the oscillator to generate a frequency very close to that for which the discriminator output is zero so that the oscillator frequency depends primarily on the potentiometer setting only. Temperature drift, hysteresis effects, and non-linear control current are all simultaneously reduced by a large factor.

By incorporating a limiter before the discriminator, the oscillator frequency can be controlled by an input voltage. This arrangement provides oscillator stabilities of better than 1 per cent and can be used effectively for telemetering purposes.



LOW FREQUENCY CLOSED LOOP CONTROL

Figure 6

The control windings of a number of units can be connected in series with the control winding of the unit shown in Figure 6. If all these are exposed to the same ambient condition, temperature drift and hysteresis will be compensated along with the unit shown in Figure 6, so that all the inductances will track. We have coined the name "bellwether" to designate such combinations of closed and open loop control. It is useful in many applications, including the one shown in Figure 7.

This family of curves shows the performance of a bandpass filter incorporating fourteen controllable inductors. The bandwidth is variable from less than 1 to over 100 kc. Hysteresis is made undetectable, and stability over a wide temperature range is obtained by a bellwether arrangement of the type just described. For high frequency filter application, relatively small inductance changes are often sufficient; and the surplus inductance change ratio can be converted into additional Q by appropriate design techniques. Units have been built with Qs of 150 at 50 mc and inductance change ratios of about 1-1/2 to 1. These components have been used as coupling elements in double-tuned r-f and i-f transformers to achieve bandwidth variation of 5 to 1 with less than a 3 db dip.

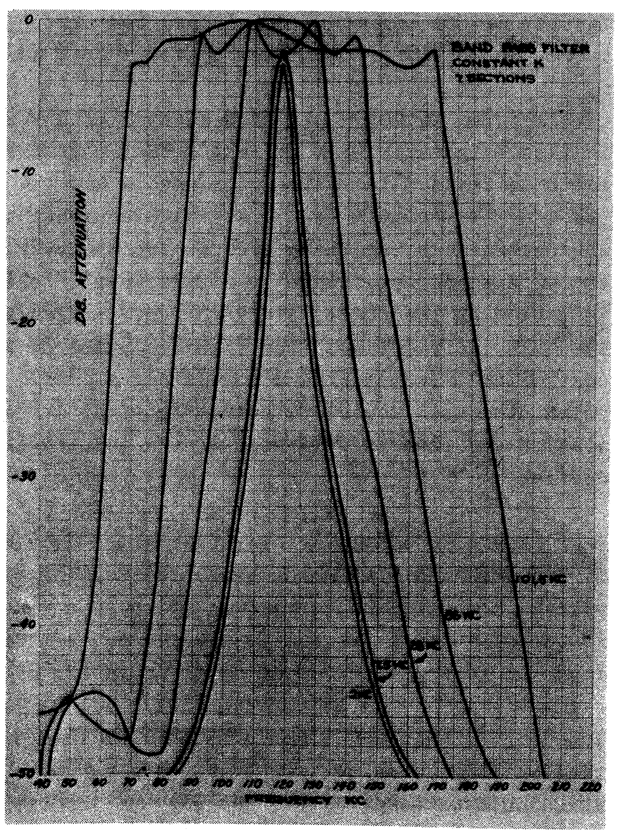


Figure 7

Controllable inductors have been used to make delay lines with controllable delay, and a typical delay time versus control current curve is shown in Figure 8. Delay changes of more than 10 to 1 are achievable at frequencies up to 1 mc. Such lines have been used for various modulation purposes and may perhaps have application on certain types of correlation computers.

The application of controllable inductors to receiver design provides many attractive features. Among these are wide frequency range, complete remote control of tuning, and of receiver bandwidth if desired, as well as instantaneous and simultaneous tuning of several remotely located receivers. Constant gain and constant r-f bandwidth over the tuning range of each band are obtained so long as the inductors are operated with Q rising proportionally to frequency. The circuit designer can use ungrounded tuned r-f circuits. Inasmuch as the controllable inductors are ganged electrically, greater freedom is possible in mechanical layout. The bellwether techniques previously discussed are very helpful in overcoming the problems of hysteresis and drift in receiver circuits. The inductors to be used in the r-f stages and the oscillator are first closely tracked, often by the means shown in Figure 9. Each of the three units is equipped with two control windings, one of which has a relatively small number of turns and is called the bias winding. The bias winding carries a fixed current adjusted by a

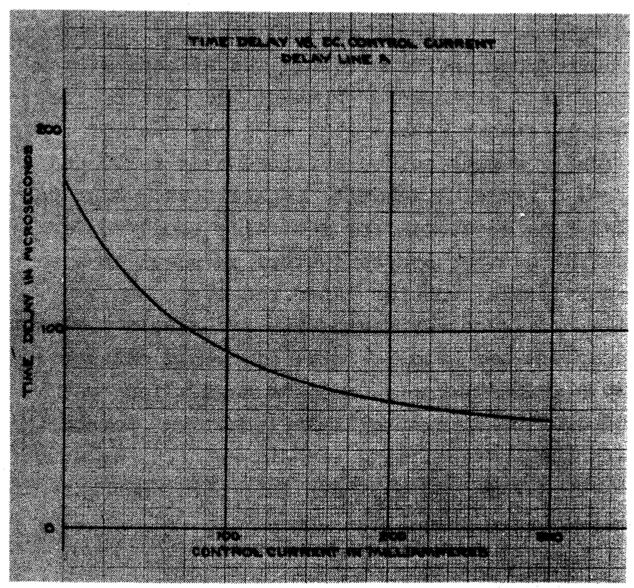


Figure 8

BASIC CIRCUIT FOR TRACKING INCREDUCTOR UNITS
(CONTROL WINDINGS IN SERIES)

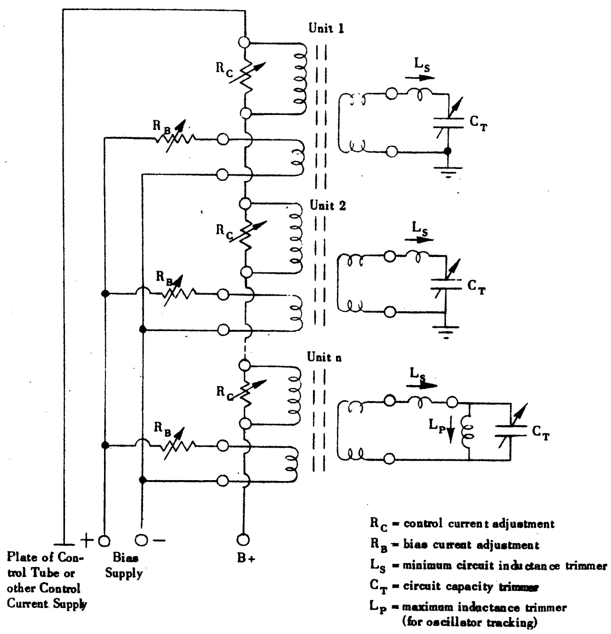


Figure 9

series resistor. Each control winding is shunted with a variable resistor. These adjustments generally permit tracking to the order of 1 per cent. The oscillator is then tracked for the chosen intermediate frequency by adjustable series and shunt inductances. Closed loop control of the type previously discussed is applied to the oscillator, and the control windings of the r-f units are placed in series with that of the oscillator. Hysteresis effects have been reduced in this way to less than 1/10 of 1 per cent with a corresponding reduction in the effects of temperature coefficient. Present indications are that frequency stabilities of 1 per cent or slightly better can be obtained over a 100 degrees C range of ambient temperatures. Four to five tube envelopes are generally required for control current and bellwether purposes in a controllable inductor tuned receiver. In a five-band receiver having two r-f stages with four inductors per band, a total of twenty controllable inductor units would be used. The cost in tubes of using controllable inductors, together with these stabilizing techniques, thus amounts to one-quarter of a vacuum tube per tuned circuit.

Controllable inductors have also been shunted across the coils of existing receivers to make possible the remote tuning of small frequency ranges such as 10 per cent.

The use of controllable inductors as non-linear elements includes switching, amplitude modulation, and signal compression or expansion. Imagine the signal winding of two controllable inductors series-connected to constitute an inductive voltage divider. Assume that the inductance change ratio is 100 to 1. With maximum control current applied to the top unit only, the voltage at the tap between the units is 99 per cent of the input voltage. With control current applied to the bottom unit only, the voltage at the tap is in the order of 1 per cent of the input voltage. In the first case, the loss of 1/10 of 1 db and in the second, 40 db. A similar arrangement using two controllable inductors, each of which has two signal windings, will produce any desired attenuation between 0.2 and 80 db. It may be used as an a-c switch or modulator or remote gain control. In switching applications, the limiting factor appears to be circuit capacity rather than any time constant inherent in the core itself and less than 0.5 microsecond has been achieved. Such switches have been used for pulse formation and may find application in telemetering. Similar arrangements may be used as amplitude modulators and will accept modulation frequencies up to several mc.

A fixed inductor can be used also with a controllable inductor in a divider arrangement which has been applied in volume compressors and expanders. The common difficulty with conventional arrangements is the thump encountered whenever there is an abrupt change in signal level. This is caused by the sudden plate current changes in the gain control tube. The signal winding of a controllable inductor is a non-linear element which does not require direct current for its operation and thus is well-suited as a gain control device.

Figure 10 shows the characteristics provided by a controllable inductor as the bottom leg of a voltage divider, the top leg of which is a fixed inductor. Between 50 and 10,000 cycles, a wide range of attenuation--about 40 db above 500 cycles--is attained. The attenuation falls off at low frequencies because of the drop in Q of the controllable inductor between 50 and 500 cycles. This could be compensated, but was not important in the application for which this unit was designed. This characteristic causes the family of

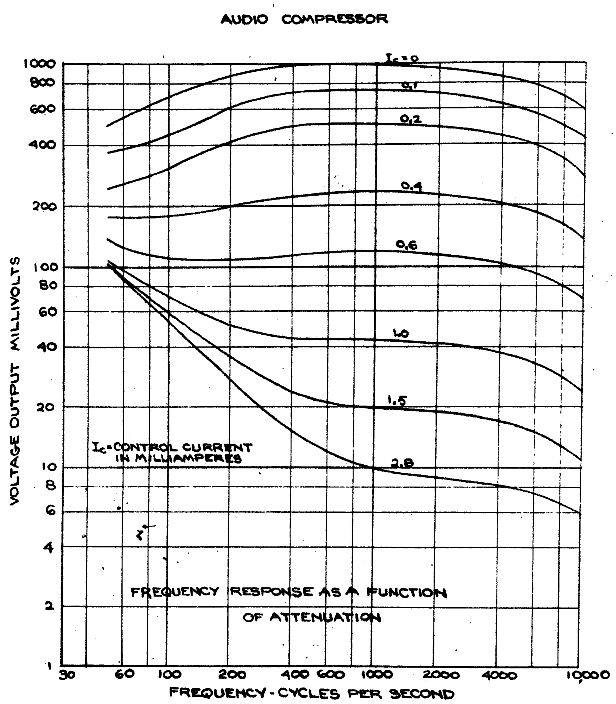


Figure 10

curves to resemble the well-known Fletcher-Munson curves. This divider was incorporated into a circuit which compressed an input variation of 40 db to 8 db at the output. Thump was not noticeable; and, in fact, there was surprisingly little subjective difference between the compressed and uncompressed signals.

A purely hypothetical receiver is shown in Figure 11. The r-f section is tuned with controllable inductors throughout. In addition, one or more stages, such as the input stage shown, are provided with controllable inductor attenuators of the type discussed previously. This enables us to obtain 40 db a-v-c range right at the input to the first tube and thus to prevent overloading of the first grid even with 100-volt signals in the input tuned circuit. It also eliminates the modulation distortion and cross-modulation that would inevitably be produced by such a large signal. One triode section following the second detector will operate four such attenuators which collectively have a range of 160 db. If our receiver is to cover the range of 100 kc to 30 mc, three bands will suffice, such as 1 to 800 kc, 800 kc to 6 mc, and 6 to 30 mc. The local oscillator also has a controllable inductor tracked to the controllable inductors in the r-f tuned circuits and with its control winding actuated from a "bellwether" circuit as we have discussed. The intermediate frequency amplifier incorporates one controllable inductor per stage to make possible a bandwidth variation of 10 to 1. For good measure, the beat frequency oscillator also utilizes a controllable inductor. We may as well equip the receiver for f-m as well as a-m detection; and then by means of a link from the discriminator to the local oscillator, we can apply afc to the local oscillator by allowing the a-f-c signal from the discriminator following the i-f amplifier to override the signal from the discriminator built into the "bellwether" circuit. The audio volume control is a controllable inductor attenuator, and this may be followed by a manually or automatically operated dynamic range expander using controllable inductors as the filter elements. We may also provide equalizing circuits in which controllable inductors make possible far greater range than can be achieved with almost any other reactance element.

This extreme example of "controllable inductorizing" has some interesting and useful properties. Except for band switches, all the functions of tuning, bandwidth adjustment, b-f-o operation, type of reception, gain, and tone quality can be remotely controlled without mechanical motion in the receiver, Except for frequency stability, which would be of the order of 1 per cent, it will equal or surpass the performance--signal to noise ratio, spurious rejection, and dynamic and tuning ranges--of a conventionally designed receiver up to 30 mc. While no one receiver is likely ever to incorporate controllable

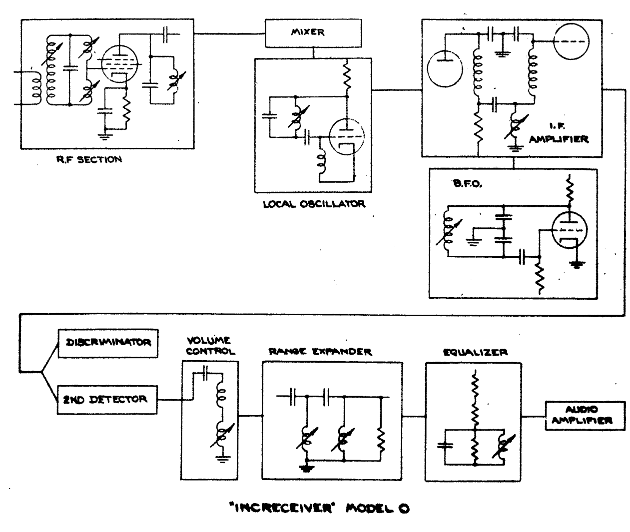


Figure 11

1BCG MONUMENT in Greenwich, Conn., now shows the names of the seven men who were the first to achieve trans-Atlantic communication by short waves, on December 11, 1921. The monument was dedicated on October 21, 1950. After the tragic death of Major Armstrong the Board of Directors decided to have the seven names inscribed on the granite shaft in honor to his memory. Here are the names: Ernest V. Amy, Edwin H. Armstrong, George E. Burghard, Minton Cronkhite, John F. Grinan, Walker P. Inman, Paul F. Godley. Copies of the 1BCG Commemorative Issue of the Proceedings, dated October, 1950, are still available from the Club at 50 cents to members, $1 to non-members.

inductors for all the purposes shown, each of the applications illustrated has its area of utility.

Most of this discussion is based on work done by the engineering personnel of CGS Laboratories, Inc. Acknowledgment is also made to many government agencies, in particular, to the Signal Corps and the Bureau of Ships, who have materially contributed to these developments.

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Members of the Radio Club of America are requested to forward any and all information and photographs, personal and professional, of Major Edwin H. Armstrong which might be of interest to posterity, to Mr. George E. Burghard, Radio Club of America, 11 West 42nd St., New York, N.Y. Mr. Burghard is Chairman of the Armstrong Memorial Committee and he is collecting material for use in the forthcoming Armstrong Memorial issue of the Proceedings. Your cooperation is requested.

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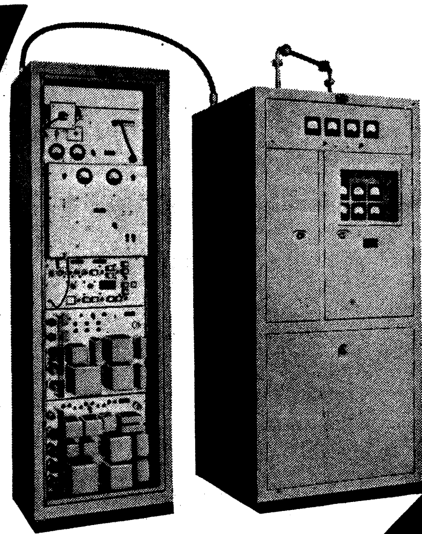

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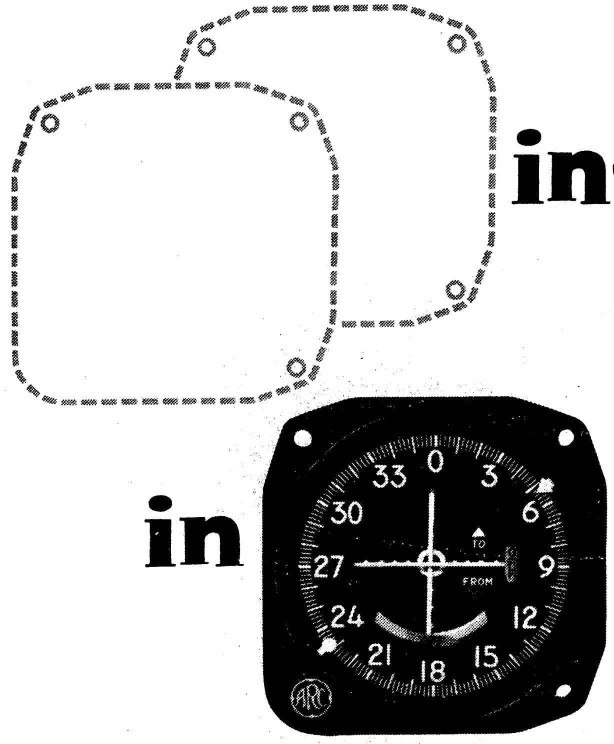

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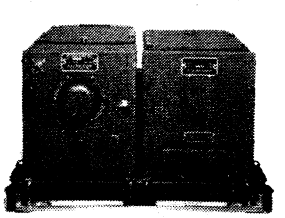
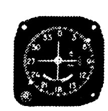


R-13B Receiver with D-10A Dynamotor B-13 Converter, E-14 Rack and M-10 Mounting



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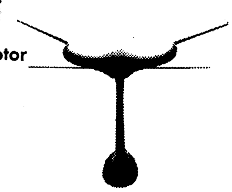

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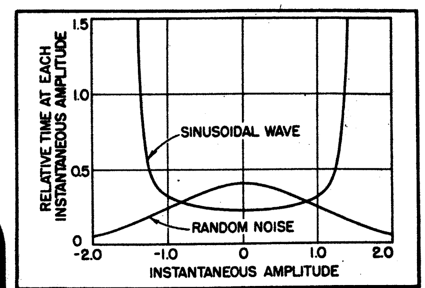
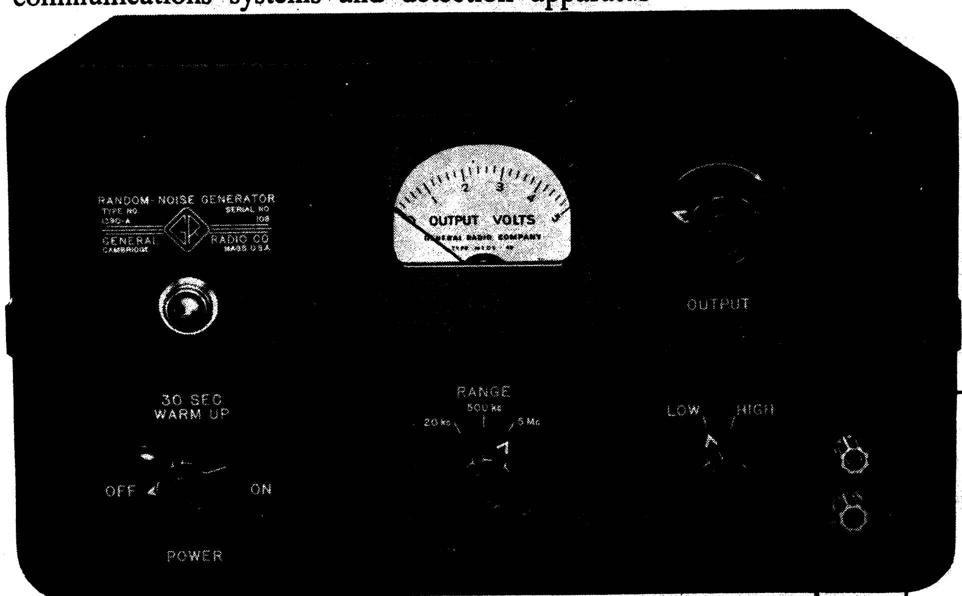
for Every Laboratory!

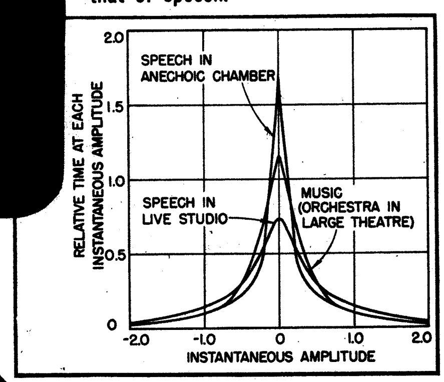
A GR ELECTRICAL NOISE GENERATOR

Electrical Noise is remarkably useful when supplied by a properly controlled generator such as G-R's Type 1390-A Random Noise Generator. Since random noise is a common form of interfering signal which limits the threshold of electrical operation, this noise source can be used to check receivers, communications systems and detection apparatus for susceptibility to interference. Controlled noise makes possible a unique approach to many problems.



The amplitude distribution of the Random Noise Generator closely approximates the normal probability distribution curve of speech, music, and many other sounds and electrical disturbances which occur naturally. Random noise, for this reason, is useful in psychoacoustic and other applications. Note that the amplitude distribution of the sine-wave is entirely different from that of speech.





a few of the Many Uses for the G-R Random Noise Generator

★ Loudspeaker and microphone response determination—room acoustics studies including reverberation tests — measurement of sound transmissions through acoustic materials used for lining walls and floors.

★ Because of its broad frequency spectrum, this generator can often simplify the search for resonant conditions — the particular frequency at which resonance occurs is determined by oscilloscope patterns at the output of the system under study.

★ This instrument may be used for demonstrating characteristics of noise and exploring the elements of statistical theory — possible errors in random sampling techniques are explored electrically.

★ The Random Noise Generator may be used for the wide-band modulation of r-f carriers — characteristics of radio and t-v receivers are determined under conditions closely approximating actual operation — cross-talk measurements on multichannel carrier systems are possible.

★ Testing recording systems. This instrument provides a much better approximation to speech and music than does the ordinary sine-wave oscillator. Furthermore, commonly used sweeping sinusoidal tests are inconvenient because of the difficulty in pre-determining the recorded frequency at any given moment in play-back. Analysis of a recorded *noise signal* is much more readily and accurately accomplished.

Type 1390-A Random Noise Generator . $240.00

Specifications

Switch Selects Either of Three Frequency Bands
30 cycles to 20 kc — *flat to within ±1 db*
30 cycles to 500 kc — *flat within ±3db*
30 cycles to 5 Mc — *flat within ±3 db to 500 kc, within ±8 db above 500 kc.*

Calibrated Output Voltmeter — *maximum output is one-volt, rms on any of three bands — accessory Type 700-P1 Voltage Divider provides output levels as low as 0.0001 volt.*

Average Spectrum Level *With 1-Volt Output* (*for one-cycle band*) — *6 mv on 20 kc band, 1 mv on 500 kc band, 0.5 mv on 5 Mc band.*

Output Impedance — *800 ohms at maximum output*

Power — *105 to 125 volts, 50 to 60 cycles*

Dimensions *are 12 x 7½ x 9¼ inches*

Net Weight *is 15 lbs.*

SINCE 1915— MANUFACTURERS OF ELECTRONIC APPARATUS FOR SCIENCE AND INDUSTRY

GENERAL RADIO Company

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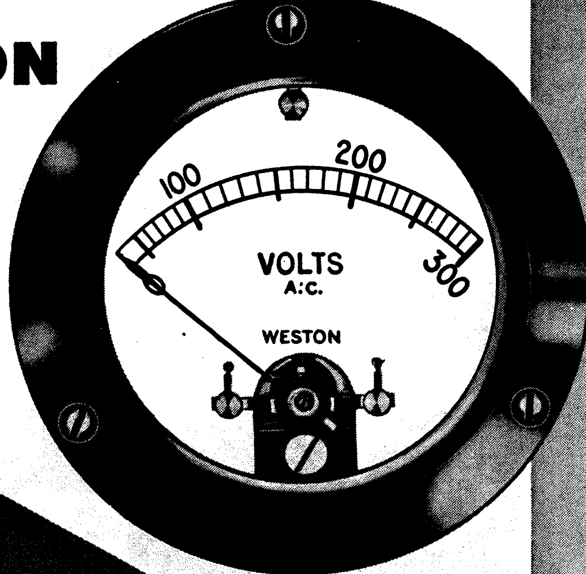
Admittance Meters ☆ Amplifiers ☆ Coaxial Elements ☆ Distortion Meters ☆ Frequency Measuring Apparatus ☆ Frequency Standards ☆ Impedance Bridges ☆ Light Meters Megohmmeters ☆ Modulation Meters ☆ Polariscopes Precision Capacitors ☆ Oscillators ☆ U-H-F Measuring Equipment ☆ Parts & Accessories ☆ Signal Generators Wave Analyzers ☆ Variacs ☆ TV & Broadcast Monitors Pulse Generators ☆ R-L-C Decades ☆ R-L-C Standards ☆ Unit Instruments ☆ Sound & Vibration Meters ☆ Stroboscopes ☆ Null Detectors ☆ Motor Controls ☆ Wave Filters ☆ V-T Voltmeters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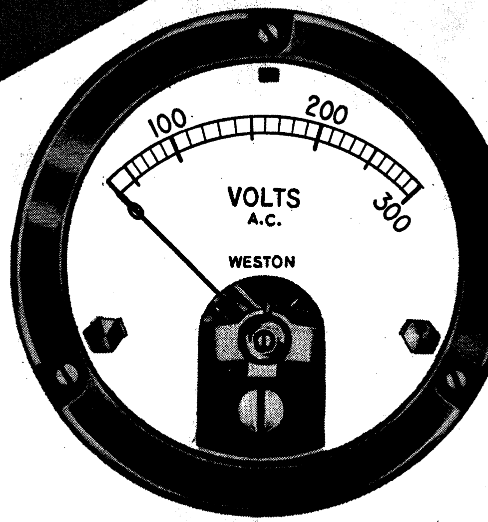
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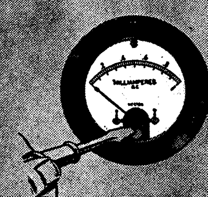
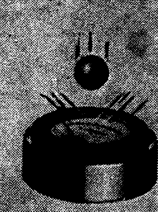
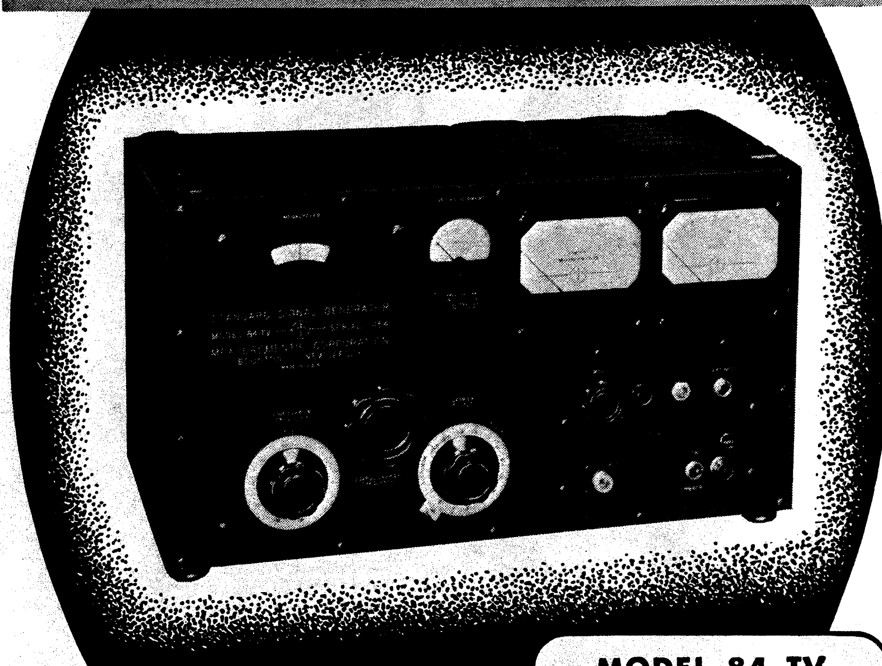




UHF Standard Signal Generator

with Low Hum Level



MODEL 84-TV

An outstanding feature of the Model 84-TV UHF Signal Generator is a built-in rectifier and filter which supplies direct current to the oscillator tube filament resulting in negligible residual hum modulation. The Model 84-TV is designed and built to the highest standards of accuracy and precision for determining the characteristics of television receivers for the UHF band, and for other equipment operating within the range of 300 to 1000 megacycles.

SPECIFICATIONS

Frequency Range: 300 to 1000 megacycles in one band. Frequency accuracy is ± 0.5%.

Output: 0.1 microvolt to 1.0 volt across a 50-ohm load over most of its range.

Modulation: Continuously variable from 0 to 30% from an internal 1000-cycle oscillator. External modulation from 50 to 20,000 cycles. Residual hum modulation is less than 0.5%.

Power Supply: 105 to 125 volts, 60 cycles, 120 watts.

Leakage: Negligible.

FEATURES

- DC operation of oscillator tube filament.
- Wide continuous frequency coverage.
- Frequency calibration accurate to ± 0.5%.
- Output dial calibrated in microvolts.
- Negligible stray field and leakage.
- Special design mutual inductance type attenuator.
- Low harmonic content.
- Low residual hum modulation.

USES

The versatility of this instrument makes it adaptable to many applications within its frequency range. Due to its high output, the Model 84-TV may be used to drive slotted lines, and other impedance measuring devices. The wide frequency coverage and accurate calibration make it particularly suitable for measuring the characteristics of UHF filters, traps, antennas, matching networks and other devices.

Laboratory Standards

MEASUREMENTS CORPORATION

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