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ULTRA LINEAR AMPLIFIERS

PART 3

by F. Langford-Smith and A. R. Chesterman

This article gives the output resistance and screen power output.

1. Output resistance

Curves of measured output resistance for type KT66, plate-to-plate, with 300 volt supply are given in Fig. 1 for two extreme values of bias (Curves A and C). Curve B is the calculated curve, using the method outlined below, using the same bias as for curve A. Curves A and B agree, within the instrument errors, for tappings of 12% or higher, thus indicating that the calculation is valid.

The method used for measuring output resistance is given elsewhere in this issue.

This measurement applies to the whole set-up, including the output transformer, plate and screen series resistors and 0.001 μF condensers from plates to screens. In our particular case, since the multi-tapped inductor L_1 (Ref. 1) did not have a secondary winding, an A & R UL 20 watt output transformer was connected with its primary in parallel with L_1, and some inaccuracy thereby introduced in readings for R_o above 10,000 ohms plate-to-plate. Since the 100 ohm plate stopper resistors are included in the measurement, the measured plate-to-plate resistance should be decreased by 200 ohms to give the valve output resistance.

The output resistance may be calculated, using the expression based on that derived by Williamson and Walker (Ref. 2.):

$$R_o = \frac{r_p}{1 + x\mu / \mu_t} \qquad (1)$$

where R_o = plate resistance (per valve)
μ = pentode mu at working point
r_p = pentode r_p at working point
x = percentage turns of tapping $\div$ 100
and μ_t = triode mu (screen connected to plate).

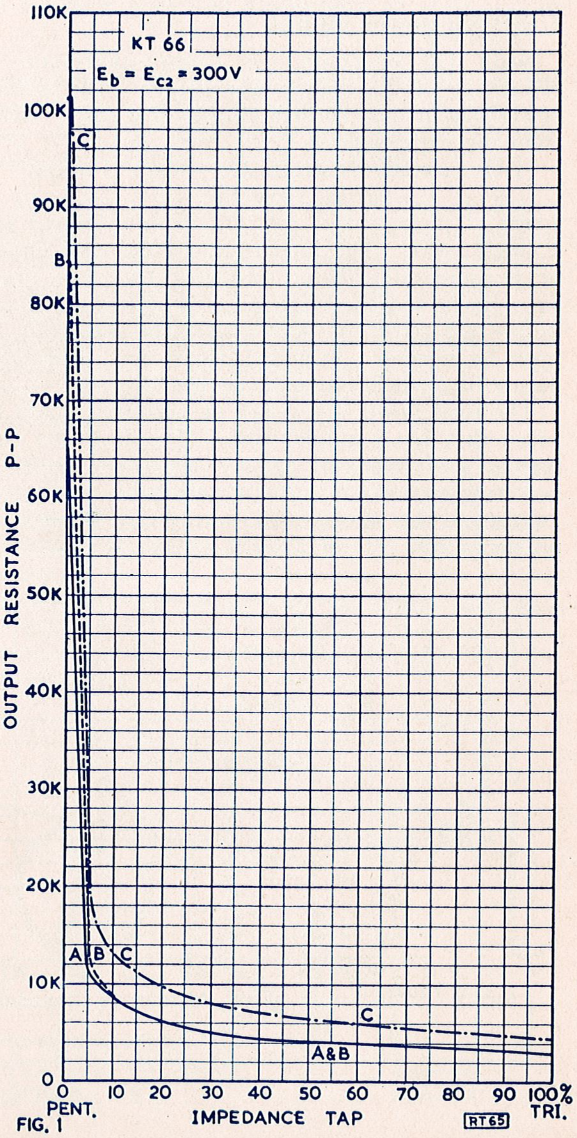

Fig. 1. Output resistance plate-to-plate versus tapping for type KT66, push-pull operation, supply voltage 300 V; (A) Measured at —26 V, R_L = 5000 ohms; (B) Calculated at —26 V; (C) Measured at —34 V, R_L = 8000 ohms (RT65).

The two valves used for the measured curves had the following average characteristics at $E_b = E_{c2} =$ 300 V, $E_{c1} = -26$ V:

$\mu = 227$; $r_p = 44{,}300$; $\mu_t = 7.7$; $\mu/\mu_t = 29.5$.

The calculations are tabulated below:

Impedance ratio	x	Output resistance per valve	Output resistance plate-plate
0%	0	44,300	88,600
5%	0.224	6,830	13,760
10%	0.316	4,300	8,600
15%	0.387	3,580	7,160
20%	0.447	3,120	6,240
100%	1.0	1,450*	2,900

* This checks well with the direct measurement (triode) 1500 ohms.

References

1. Part 1 of this series, Radiotronics, May 1955, p. 60, Fig. 6.
2. Williamson & Walker "Amplifiers and Superlatives", W.W. 58.9 (Sept., 1952), 357.

2. Screen power output

With UL operation the screen contributes a percentage of the total power output. The screen power output may be determined for a single valve from the expression:—

P.O. (screen) = screen a.c. voltage × screen a.c. current

where all these values refer to those measured on a single valve. The screen a.c. voltage may either be measured directly or calculated from the plate a.c. voltage and the turns ratio of the transformer. Before the screen a.c. current can be measured, it must be separated from the screen d.c. current by means of a choke-capacitor network.

The total power for a pair of push-pull valves is twice that for a single valve. The fact that the screen was delivering power and not receiving power was checked by noting that the screen a.c. voltage at the screen itself was greater than that on the supply side of a series resistor.

Measured results are shown in the curves of Fig. 2, for type KT66 under stated conditions. Curve A shows that the percentage of total power contributed by the screen varies from 2.3% at the 5% tap, steadily increasing to 7.8% for triode operation. Curve B shows that the total power contributed by the screen under the selected conditions increased from less than 4% with a 5000 ohm load to 5.85% with a 10,000 ohm load.

The impedance (R_s) into which a single screen works was calculated from the known screen power output.

Let I_s = screen a.c. current per plate

and E_s = screen a.c. voltage per plate.

Then P.O. (screen) $= E_s I_s = I_s^2 R_s$.

Therefore $R_s = E_s/I_s$.

For example, with type KT66, 300 volts, R_L = 5000 ohms plate-to-plate, 13 watts, 20% tap: E_s = 57 V per valve

Measured I_s = 4.5 mA per valve

Screen power output per valve $= E_s I_s = 0.256$ W

$R_s = E_s/I_s$ = 12,700 ohms per valve.

Also screen power output per valve $= (I_s)^2 R_s =$ 0.256 W, agreeing with the result obtained by the other method.

Note that this calculated value of R_s, the impedance into which a single screen works, is considerably greater than the proportion of the load resistance R_L which is reflected through the transformer to the tapping point. This result is to be expected from fundamental network analysis, in which two generators feed a common load resistance in phase; each generator "sees" a higher load resistance than the actual load. For those who are interested, a simple analysis along these lines will appear in a future issue.

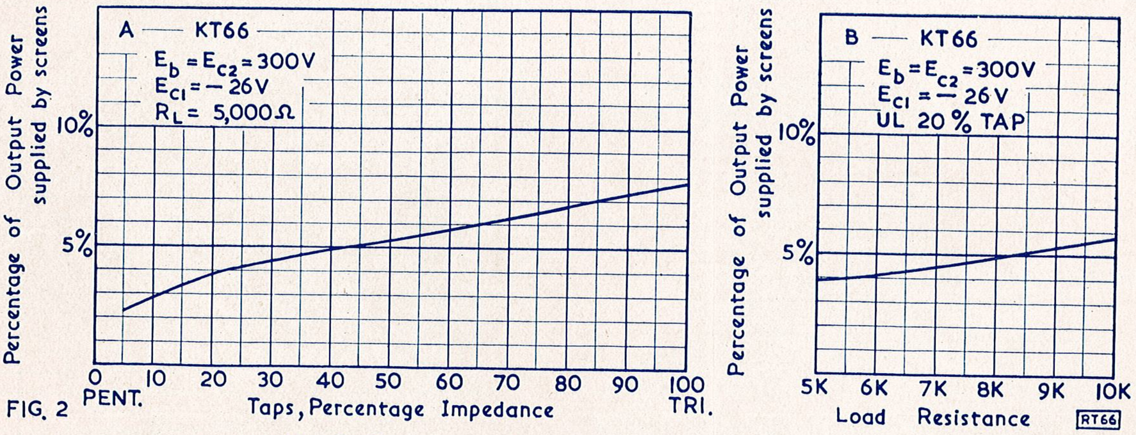

FIG. 2

Fig. 2. Percentage of output power supplied by the screen, for type KT66; (A) versus tapping point; (B) versus load resistance (RT66).

SOME EFFECTS OF NEGATIVE FEEDBACK ON OUTPUT RESISTANCE

by E. Watkinson

1. Measuring amplifier output impedance

What appears to be a simple method of measuring the output impedance of an amplifier, with or without feedback, is shown in Fig. 1. A voltage E is developed across the output load through a resistor R which is much greater in resistance than the output impedance of the amplifier. By determining the current I flowing in R and the voltage E, the parallel impedance of the amplifier output impedance R_o and the load resistance R_L can be obtained. Since the value of R_L is known, or can be determined by the same method, R_o can be simply calculated.

Analysis of this circuit shows that

$$I = \frac{E}{R_{L3}} + \frac{E}{r_{p3}} + \frac{E\beta A_1 A_2 \mu_3}{R_{L3} + r_{p3}}$$

where $R_1 + R_2 \gg R_{L3}$

$$\beta = \frac{R_2}{R_1 + R_2}$$

$A =$ stage gain

and $g_{m1}R_2 \ll 1$.

Since the amplifier output resistance with feedback $R_o' = \dfrac{E}{I}$

$$R_o' = \frac{E}{\dfrac{E}{R_{L3}} + \dfrac{E}{r_{p3}} + \dfrac{E\beta A_1 A_2 \mu_3}{R_{L3} + r_{p3}}}$$

$$= \frac{1}{\dfrac{1}{R_{L3}} + \dfrac{1}{r_{p3}} + \dfrac{\beta A_1 A_2 \mu_3}{R_{L3} + r_{p3}}}$$

Thus R_o' is the resultant of three parallel resistances, R_{L3}, r_{p3} and $\dfrac{R_{L3} + r_{p3}}{\beta A_1 A_2 \mu_3}$, and the effect of the feedback is to add a resistance $\dfrac{R_{L3} + r_{p3}}{\beta A_1 A_2 \mu_3}$ in parallel with R_{L3} and r_{p3}.

The conventional solution of output impedance in the presence of feedback shows that the effect of feedback is to add a resistance of $\dfrac{r_{p3}}{\beta A_1 A_2 \mu_3}$ in parallel with the output circuit. Especially in the case of triode output valves, for which R_{L3} and r_{p3} may be of the same order, the difference between these two solutions may be significant.

The reason for the difference is that in Fig. 1 the voltage E is set up across R_{L3} and r_{p3} in parallel, whereas in the conventional analysis E is a voltage in series with R_{L3} and r_{p3} as in Fig. 2. Since only the latter condition simulates the effect of voltages developed in the voice coil of a speaker when "hanging on" at its resonant frequency, it is the correct method for determining amplifier output impedance.

When the circuit of Fig. 2 is used for output impedance determination, the source impedance of E must be much less than that of the series connection of R_{L3} and r_{p3}, which may be difficult when measuring on the secondary side of the output transformer, but which can be readily arranged on the primary side. A suitable step-down transformer may be used for measurements on the secondary side.

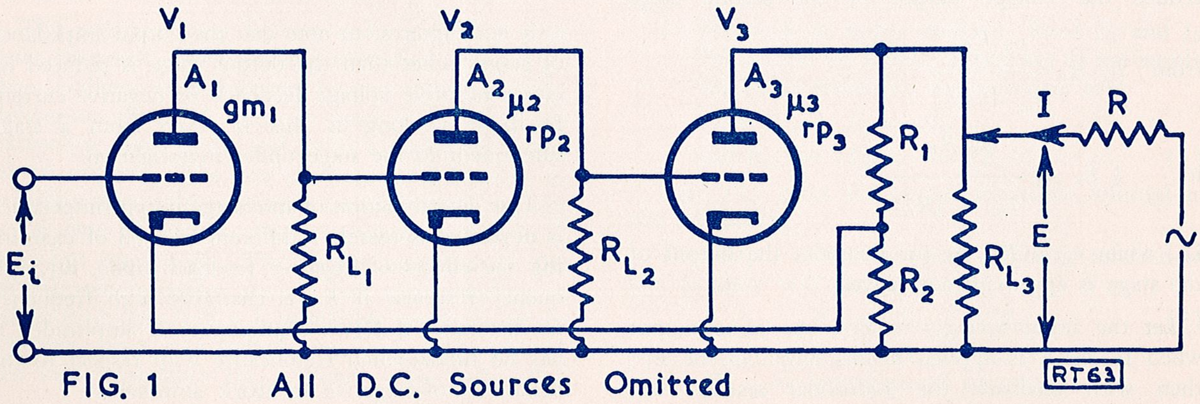

FIG. 1 All D.C. Sources Omitted

2. Output impedance of other amplifier stages

Although the effect of negative feedback on the output impedance of the output stages of amplifiers is commonly discussed, its effect on the apparent output impedance of other stages is never referred to.

As shown above, it is necessary, in determining output impedance, to use a reasonably close approximation to actual operating conditions if a correct analysis is to be made. For example, the method of inserting a voltage in series with the load as shown in Fig. 2 is not applicable to stages other than the output stage because in operation such series voltages do not appear.

However, changes in the impedance of R_L are met with, for example, if a following stage is driven into grid current or if R_L has a reactive component. Thus a determination of the variation in output voltage with changes in the value of R_L may be useful.

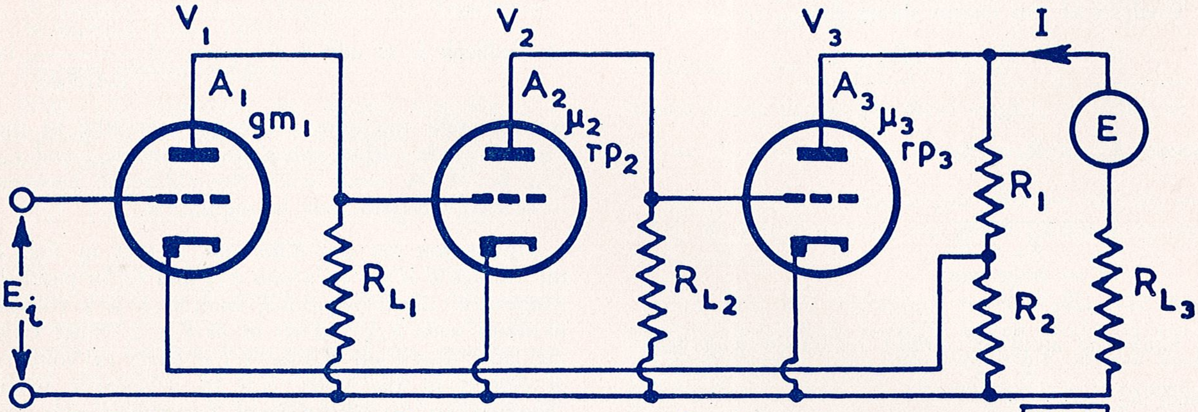

FIG. 2 All D.C. Sources Omitted

In Fig. 1 let a resistor be connected in parallel with R_{L2} which halves its effective resistance. In the absence of feedback the additional resistor will reduce the voltage output of the second stage

from $E_i \, A_1 \dfrac{\mu_2 \, R_{L2}}{r_{p2} + R_{L2}}$

to $\tfrac{1}{2} \, E_i \, A_1 \dfrac{\mu_2 \, R_{L2}}{r_{p2} + \tfrac{1}{2} R_{L2}}$

i.e., when $r_{p2} \gg R_{L2}$ as for pentodes the output of the stage is approximately halved.

Let the input voltage, to give the same output when feedback is applied to the amplifier, be E_i', then with feedback the additional resistor will reduced the output voltage of the second stage

$$\text{from} \quad \frac{E_i' \, A_1 \dfrac{\mu_2 R_{L2}}{r_{p2} + R_{L2}}}{1 + \beta A_1 A_3 \mu_2 \dfrac{R_{L2}}{r_{p2} + R_{L2}}}$$

$$\text{to} \quad \frac{\tfrac{1}{2} \, E_i' \, A_1 \dfrac{\mu_2 R_{L2}}{r_{p2} + R_{L2}}}{1 + \tfrac{1}{2} \beta A_1 A_3 \mu_2 \dfrac{R_{L2}}{r_{p2} + R_{L2}}}$$

Thus, when a reasonable degree of feedback is used, the effect of the shunting resistor on the output of the driver stage is small, which is another way of saying that the output impedance of the driver stage is low. The overall feedback has therefore reduced the output impedance of the second stage.

Similar results would be obtained by calculating the effect on any other stage.

It is of interest to note that the output impedance of stages other than the output stage is reduced by either negative voltage feedback or negative current feedback so long as this is taken from a stage subsequent to the stage under investigation.

This determination of interstage output impedance is nevertheless merely a different method of examining the effects of negative feedback upon, say, frequency response if R_L is changing with frequency or distortion if R_L is changing with amplitude. It has no fundamental significance with respect to the behaviour of negative feedback amplifiers.

MODERN METHODS OF TESTING AMPLIFIERS

by F. Langford-Smith and A. R. Chesterman

A comprehensive series of articles is planned to cover all aspects of testing amplifiers, giving full details of the equipment being used for such purposes in the Radiotronics Laboratory.

1. Output resistance

An article providing the theoretical basis for this method of measurement appears elsewhere in this issue. The measurement may be made either on the primary or secondary side of the transformer. The primary side requires an a.c. milliammeter with a 0-10 mA range, while the secondary side requires one with a 0-100 mA range. Measurements on the secondary side are usually more convenient, especially for complete feedback amplifiers, and are therefore normally used in the Radiotronics Laboratory.

The circuit diagram of the test set-up is Fig. 1, which may be applied to either single-ended or push-pull amplifiers, with or without feedback. The load R_L may be either a loudspeaker voice coil or a resistive load; different values of R_{os} will be obtained at certain frequencies with the alternative forms of load. If an amplifier is to be used only with one loudspeaker, then true results will be obtained by using this loudspeaker as the load. In other cases the choice is optional. It is desirable to carry out the test over the whole audible range, from 30 to 10,000 c/s.

The published value appears to be measured at about 1000 c/s, where it is usually a minimum. However, the most important value is at the loudspeaker bass resonant frequency since this determines speaker damping and "hangover". In all amplifiers the output resistance rises at very low frequencies owing to the combination of reduced feedback and transformer losses. Hence, if it is desired to limit readings to the minimum, tests may be made at 1000 c/s and at a frequency in the vicinity of the loudspeaker bass resonant frequency (say 30 or 50 c/s).

The oscillator may be any audio oscillator with total harmonic distortion not exceeding about 1%. The oscillator amplifier may be any convenient one delivering about 10 watts or more with THD not exceeding about 1%, and with a damping factor of 10 or more. The one used in our laboratory is a Williamson with an output transformer T_1 having a 3.6 ohm secondary; this is correctly loaded by a 3.6 ohm resistor R_1. The output resistance of the Williamson amplifier on the 3.6 ohm winding is about 0.12 ohm which is negligibly small for 10 to 15 ohm voice coil impedances, and about 5% of the load impedance for 2.5 ohm voice coils. The voltage E across the secondary of T_1 is measured by a valve voltmeter (Avo Electronic Testmeter), although a rectifier type voltmeter would do equally well. The applied voltage is about 1 to 3 volts for 10 to 15 ohm voice coils. The applied voltage should not exceed half that for maximum power output.

The current I through the series circuit is measured by a rectifier type meter (e.g., Avo Model 8) on the 100 mA range. The desirable bottom limit for accuracy on this range is 20 mA.

The procedure in taking measurements is:—

1. Switch S in lower position. Read E_1 and I_1. Let Z_1 be the impedance of R_L in series with the output impedance of the oscillator amplifier.
   Then $Z_1 = E_1/I_1$.

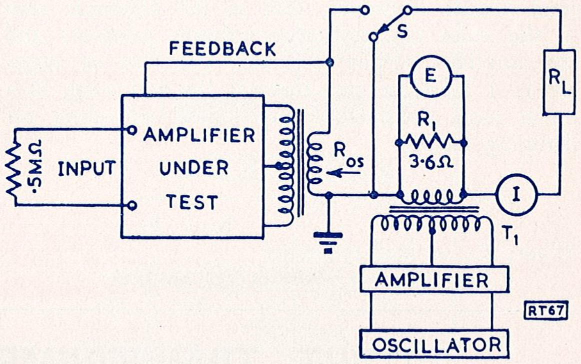

Fig. 1. Circuit diagram of test circuit for measuring the output resistance of an amplifier (RT67).

2. Switch S in upper position. Read E_2 and I_2. Let R_{os} be the output impedance of the amplifier being tested, on the secondary side.
   Then $R_{os} + Z_1 = E_2/I_2$
   and $R_{os} = (E_2/I_2) - (E_1/I_1)$ (1)

Eqn. (1) gives the output resistance referred to the secondary.

The output resistance (plate-to-plate) referred to the primary will be given by

$$R_{op} = R_{os} Z_{p\text{-}p}/Z_s \qquad (2)$$

where $Z_{p\text{-}p}$ = impedance plate-to-plate
and Z_s = impedance of secondary.

Damping Factor - A New Approach

by F. Langford-Smith

The following letter has been sent to the Editor of "Wireless World", and has been accepted for publication in their August issue. It raises a matter of considerable importance to all those interested in amplifiers.

As the one originally responsible for introducing the term "damping factor" (1), the writer feels some responsibility for finding an alternative form now that we are so deeply in the morass. The term had many shortcomings but it could, at least, be used safely so long as it was always finite and positive. The commercial release of amplifiers with negative damping factors has been very confusing to engineers, to say nothing of the general public. For an increase of 22% in total circuit damping, the "damping factor" increases from 10 to infinity, then returns back from —infinity to —10. All these extraordinary changes in the damping factor would lead one to believe that something important was happening. In reality, nothing has happened except a slight and steady increase in the total damping. The tricks played by the so-called damping factor are due merely to an unfortunate choice of definition. With this definition, instability occurs when the damping factor $\leqq -1$.

The total circuit damping is a function of the total circuit resistance, that is the algebraic sum of the voice coil resistance (always positive) and the amplifier output resistance (positive or negative). I therefore put forward the following as a much more satisfactory and logical substitute for damping factor:

$$\text{Damping ratio} = \frac{R_L}{R_L + R_o}$$

Where R_L = load resistance
R_o = output resistance of amplifier

and where both R_L and R_o are referred to the same side of the transformer.

The following table is for $R_L = 15$ ohms and is purely as an example:

It will be seen that the proposed damping ratio is positive and finite so long as instability does not occur. It is also proportional to the actual damping in the circuit. It appears to be the only available function with all the desired qualities.

R_o ohms	$R_L + R_o$ ohms	Damping Factor $= R_L/R_o$	Damping Ratio $= R_L/(R_L + R_o)$
+75	+90	+0.2	0.167
+ 3	+18	+5	0.83
+ 1.5	+16.5	+10	0.91
+ 0.15	+15.15	+100	0.97
+ 0	+15.0	∞	1.0
— 0.15	+14.85	—100	1.01
— 1.5	+13.5	—10	1.11
— 5.0	+10.0	—3	1.5
—12.0	+ 3.0	—1.25	5.0
—13.6	+ 1.4	—1.1	10.7
—14.3	+ 0.7	—1.05	21.4
-15.0 on verge of instability.	0	—1.0	∞

1. Langford-Smith, F., "Radiotron Designer's Handbook", 3rd ed., 1940.

OUTPUT TRANSFORMERS - A USEFUL DEVICE

by F. Langford-Smith

The owner of an amplifier and output transformer is sometimes faced with the necessity for changing the loudspeaker to one of different voice coil impedance.

In some cases this may necessitate purchasing a new output transformer, but when the difference in impedance is small (e.g., from 15 to 12.5 ohms or vice versa), this drastic step is not necessary.

The impedance of a loudspeaker changes enormously over the audio frequency range — a change of 10 to 1 being quite normal and sometimes exceeded by high efficiency loudspeakers. Consequently the "nominal" impedance is rather indefinite and, in any case, only holds over a very limited range. In addition, feedback amplifiers have the useful property of largely counteracting the rise of distortion due to a high impedance load, by the increased feedback.

If only medium fidelity is required, the change in loudspeaker may be made without any other change, at the cost of an increase of the distortion. This increase in distortion is usually greater, with pentode output valves, when the load resistance is increased (e.g., from 12.5 to 15 ohms) than when it is decreased by the same percentage.

This increased distortion may be completely eliminated by a series or shunt resistor to give correct loading. Take, for example, the case when a transformer with a 12.5 ohm secondary is to be used to drive a 15 ohm voice coil. Using Ohm's law, a resistor of 75 ohms shunted across 15 ohms will give a total resistance of 12.5 ohms, and the resistor will carry 17% of the total amplifier power output. This loss in power is less than 1 db and is quite inaudible.

In the general case, when a shunt resistor is required, let R_{L1} = secondary load in ohms,

R_{L2} = voice coil impedance in ohms
and R_1 = shunt resistor.

Then $R_1 = R_{L1}R_{L2} / (R_{L2} - R_{L1})$ (1)
and the power loss in R_1 will be
$W = (R_{L1} / R_1) \times$ amplifier power output. (2)

When it is necessary to add a series resistor, that is, when R_{L1} is greater than R_{L2}, the value of the series resistor R_2 is given by:

$R_2 = R_{L1} - R_{L2}$ (3)
and the power loss in R_2 will be
$W = (R_2 / (R_2 + R_{L2})$. (4)

LINKS IN THE AUDIO CHAIN

by F. Langford-Smith

It is always helpful to put things in their right perspective. ~~developed across the output load through a resistor R~~ The purpose of radio broadcasting is to bring speech or music from the studio or concert hall to the listener; it begins with audio in one place and it ends with audio in the listener's ear. Radio broadcasting is only the means used to achieve this end. A typical chain, extending from the broadcast studio to the listener, is illustrated in Fig. 1. As shown here, the chain has six audio links, and only two radio links in the middle.

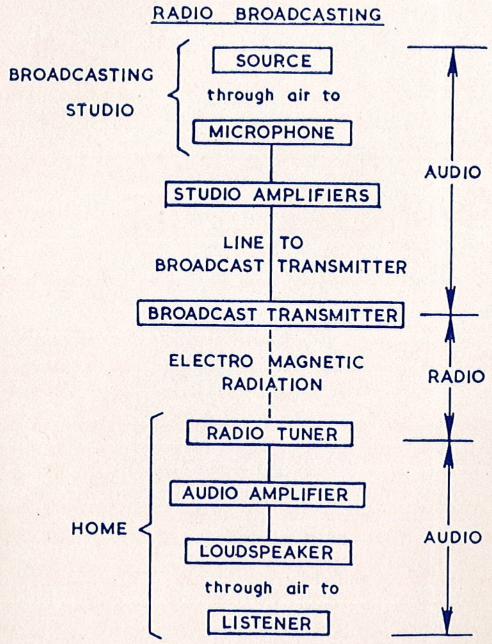

FIG. 1

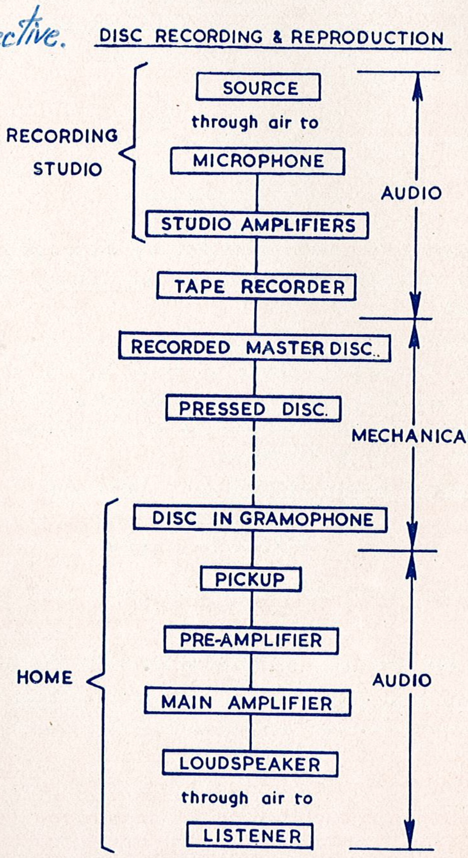

FIG. 2

A very similar chain may be pictured in disc recording and reproduction, Fig. 2. Here we have nine audio links, with three mechanical links in the middle.

The idea of the audio chain was put forward by an American writer some time ago, but it is such a good idea that it is worth sharing with others.

REDUCING VOLTAGE OUTPUT OF CRYSTAL PICKUPS

Many crystal pickups generate voltages of several volts on high level recordings, and this may be sufficient to overload the first amplifying valve if no volume control is used between the pickup and the first grid. This overloading can be prevented by either of two methods:

1. Using a fixed resistance voltage divider network between the pickup and the first grid.

2. Using a capacitor shunted across the pickup terminals. This has the effect of minimizing any attenuation of response at frequencies below about 100 c/s, since it decreases the total source impedance. This effect on the bass response may or may not be desirable in a particular case.

Alternatively, the larger total capacitance would permit a smaller value of load resistance to be used for the same frequency response. The voltage output is given by:

$$E_2 = E_1 C_1 / (C_1 + C_2).$$

Where E_1 = normal voltage output of pickup,
E_2 = output from pickup with C_2 shunted across its terminals,
C_1 = capacitance of crystal,
and C_2 = capacitance shunted across pickup.

For example, if $C_2 = C_1$, the voltage will be halved.

Typical values of C_2 are from C_1 to $5C_1$, giving values of output voltage E_2 from 0.5 to 0.17 E_1.

Values of C_1, the crystal capacitance, are usually published by the manufacturer of the pickup. Some values are given below:—

Ronette Model	TO-284-N	1800 $\mu\mu$F
	TO-284-OV	1500
	TO-284-P	1500

Some Notes on Class B Amplifiers

by F. Langford-Smith

Class B amplifiers are usually avoided when even fair fidelity is required owing to the large amount of distortion (usually greater at medium levels than at maximum output), the difficulty of applying negative feedback, and the tendency towards parasitic oscillation at points in the cycle where plate current cut-off occurs.

A recent design (Ref. 1) seems to overcome most of these disadvantages, if its claims can be substantiated. Cathode follower push-pull drivers are used, thus avoiding the driving transformer and permitting the use of feedback — this is, of course, not novel. The output valves (type 6N7) were operated at a higher current than normal (12-15 mA total) and the plate load resistance was much higher than usual (20,000 ohm plate-to-plate). In addition, the cathode follower load resistors were so adjusted as to cause the cathode follower to cut off before the output valves cut off. The driver valve used was type 6SN7, and the cathode-to-cathode load consisted of 4700 ohms fixed, 10,000 ohm potentiometer, in series with 4700 ohms fixed. The grid return was taken to the moving contact which was adjusted to give balanced clipping on both sides.

The total harmonic distortion was 1.3% at 10 watts with 15 db negative feedback.

A similar arrangement could be used for Class AB_1 and AB_2 operation.

Reference

1. J. Julie "Back to Class B for home use" Audio 39.3 (March 1955) 19.

Corrections Noted

ERRATA

In this issue, page 83, Links in the Audio Chain, line 2, should read: perspective. The purpose of radio broadcasting is

June issue, page 74, column 1, line 2 omitted this should read: QUAD II and other amplifiers (Ref. 1 and 2).

Editor .. .. D. Cunliffe-Jones

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