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A 4.5 Watt Single-Ended Amplifier

(By the Staff of the Radiotronics Laboratory)

A two-stage single-ended amplifier incorporating feedback tone-control, with some novel features and performance distinctly above the average.

We were recently confronted by a request to design an inexpensive but good 4.5 watt amplifier for operation from a crystal pick-up and suitable for driving a wide-range loudspeaker. The type used initially was M.S.P. 12 inch woofer AU58/12P39 with 6 inch tweeter M.S.P. 20766 6PU. The design holds for any wide range loudspeaker, or, of course, for any conventional speaker with good bass response. The possible alternatives were examined carefully, since the only real snag is in the tone control. It is obvious that some very effective form of treble attenuation is required to be able to cut down the scratch level from old records. This is made more difficult by the use of an extended range loudspeaker. Experiments showed that an attenuation of well over 20 db was necessary over the range from 8000 to 15,000 c/s.

Now a two-stage amplifier with feedback is quite a straight-forward design problem, provided that the feedback is not used for tone control purposes. But when we try to incorporate feedback tone-control, although the "sine-wave" performance may appear to be satisfactory, the real shortcomings of amplifiers are shown up by "square-wave" testing.* The initial results obtained with square-wave testing were so distressing that the alternative was seriously considered—to insert an additional stage purely for tone control purposes, without feedback, with its output connected to the input terminals of a two-stage "flat" feedback amplifier. However, there is a wide interest in two-stage amplifiers, and so we tackled the task of making the best possible two-stage amplifier, using Radiotron types 6AU6 and 6AQ5 (or 6V6-GT), and this article shows with what success.

The whole design centres around the feedback system. Feedback may be taken from two points, the 6AQ5 plate and the secondary of the output transformer. The former is simple to apply and does not introduce instability problems, but it does not reduce transformer distortion — quite a serious item in this case — and it somewhat accentuates hum. Feedback from the secondary is regarded by some as the ideal, but it cannot be used on its own with any large degree of feedback, unless very expensive output transformers are used, without danger of instability. This actual or incipient instability is largely due to the large phase shift which occurs in any transformer, between primary and secondary, at very high frequencies. Thus "negative" feedback actually becomes positive feedback at the extremes of frequency. The effects of the positive feedback at high frequencies are shown, on a square wave input of say 5000 c/s, by the extent of the overshoot and the length of time taken for the oscillation to die down.

The circuit diagram of this amplifier is shown in Fig. 1, and it will be seen that a combination of plate and secondary feedback has been used to get some of the advantages of both. The phase angle obtained is intermediate between that at the plate and on the secondary. With the tone control in the "flat" position, the total gain reduction at 1000 c/s is 9.8 times (19.8 db), this being the highest practicable value.

With the tone control in the extreme bass position there is an additional 22 db of feedback at 10,000 c/s.

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* *An article on square wave testing will appear in a future issue,*

The RC network shunted across the primary of the output transformer is for the purpose of reducing or eliminating the overshoot and damped high-frequency oscillation when tested with a square wave. The linearity characteristic is shown in Fig. 2, which shows that the maximum input voltage for low distortion is 0.35 V r.m.s. The linearity is quite good up to 2.5 watts in the secondary. The overload characteristic on listening test is very good and smooth, with no objectionable features.

The manufacturer's transformer efficiency rating is about 80%, and this is confirmed quite closely by the measurements on primary and secondary. The reduction in THD due to feedback averages 19.7 db between 2 and 3 watts output, a remarkably close approach to the 19.8 db applied feedback. From (C) the power output at 75 c/s is 3.1 W at 2% THD, or 1.9 W at 1%. The reduction in THD at 75 c/s due to feedback is 19.3 db at 3 watts. From (D) the power output at 5000 c/s is 2.85 W at 2% THD, or 2.05 W at 1%, while the reduction in distortion due to feedback is 15.3 db at 2 W. This slight reduction in power output for specified values of distortion at low and high frequencies due to reactive effects is, of course, to be expected, as is also the falling off in the reduction of distortion by feedback. Somewhat better values would have been expected from the use of a single secondary feedback loop, but this was ruled out as being impracticable in the case being considered.

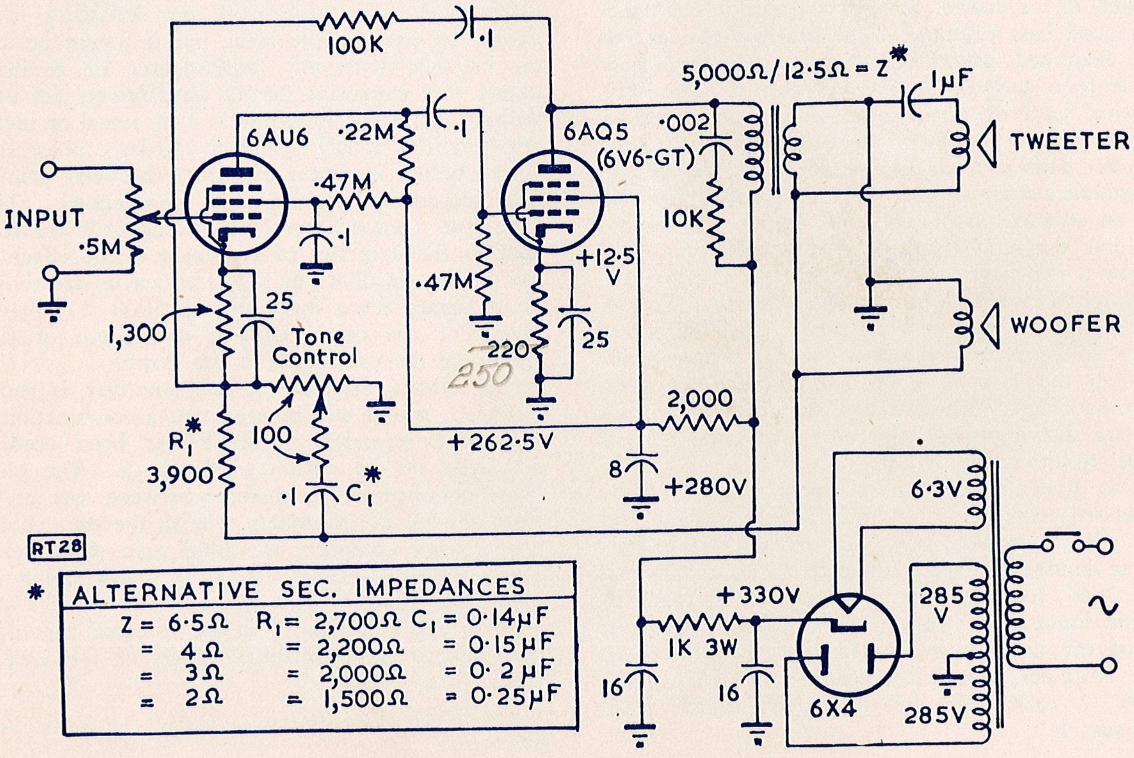
The frequency response characteristics of the amplifier with transformer C are shown in Fig. 4. Curve 1 shows the response without feedback. Curve 2 shows the response with feedback, with the tone control flat. Curve 3 shows the effect of secondary feedback only, by removing feedback from the plate. This gives a peak of about 3.5 db at 35,000 c/s, which would have been even higher if the total effective feedback had been increased to the same value as for Curve 2. Curve 4 shows the frequency characteristic with the tone control in the extreme bass position. Of course, by a suitable adjustment of the tone control, any intermediate characteristic between 2 and 4 may be obtained.

The response characteristics in Fig. 4 are only drawn down to the lowest frequency available from our oscillator. A special low frequency oscillator going down to about 1 c/s. is under construction, and will shortly be available for our tests.

It is our opinion that no feedback amplifier should show a peak in the high frequency region higher than the level at 1000 c/s, and that there is no necessity for it to do so, since design methods are available to prevent its occurrence. By this means the amount of overshoot on square waves is reduced, although overshoot can occur even without a high frequency peak.

In view of the limited range of audible frequencies, the question might well be asked why take the trouble to measure the response up to frequencies of the order of 500 Kc/s. The reason is that there are normally peaks in response anywhere between

Fig. 1. Circuit diagram of 4.5 watt amplifier with feedback tone control. All resistors ½ watt unless otherwise stated. 6AQ5 plate and screen voltages to cathode 250 V. [RT28.]



* ALTERNATIVE SEC. IMPEDANCES

Z	R₁	C₁
Z = 6·5Ω	R₁ = 2,700Ω	C₁ = 0·14μF
= 4Ω	= 2,200Ω	= 0·15μF
= 3Ω	= 2,000Ω	= 0·2μF
= 2Ω	= 1,500Ω	= 0·25μF

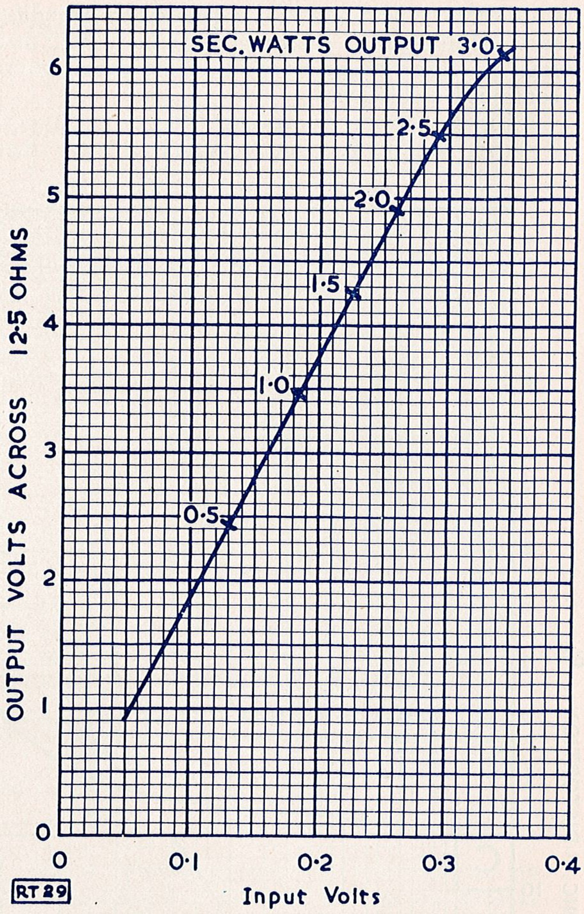


Fig. 2. Linearity characteristic using transformer C. [RT29.]

40 and 300 Kc/s, and these peaks may result in instability and "ringing" on transient waveforms. These transient waveforms occur in almost any musical reproduction. For most designers with limited equipment it is possible to use a square wave generator as a reasonably satisfactory substitute for wide-range frequency tests.

At the bass end a peak of 6.3 db at 25 c/s occurs with the tone control flat, which increases to 7.5 db when turned to "bass". This has been found to provide a small but acceptable degree of bass boosting. The response falls off quite rapidly below 25 c/s, and we have not found any need for a special rumble filter. However, if rumble is experienced, it would be very simple to decrease the extreme bass response of the pickup by reducing its load resistance.

These curves were taken without the tweeter connected, in order to make a stiffer test. The tweeter, as shown in this circuit, reduces the impedance at high frequencies and so gives better-looking curves.

Curve 2 shows an antinode at 160 Kc/s, followed by a return to the normal attenuation characteristic at 200 Kc/s. This is a function of the transformer, and occurs even without feedback (Curve 1). Transformer C was used for the curves in Figs. 4 and 5 because, of the three transformers tested, it had the best high frequency characteristics. Transformer A had a somewhat similar shape of the response characteristic, and is quite suitable for this application. But transformer B, with the primary wound in two sections, gives a series of valleys and peaks above 160 Kc/s, with a high peak at 850 Kc/s, so that this form of construction is not recommended.

The feedback versus frequency characteristics, Fig. 5, are obtained by subtracting the feedback curves in Fig. 4 from Curve 1 (without feedback). Curve 5 is for tone control flat; positive feedback occurs below 30 c/s and above 60 Kc/s. Curve 6 is for feedback from secondary only, with, of course, reduced degree of feedback — it would extend further into the positive region if the secondary feedback were increased to the same level. Curve 7 is for tone control "bass"; positive feedback occurs below 33 c/s and above 125 Kc/s. At high frequencies the peak is + 20 db with the tone control "flat" and less than + 7 db with tone control "bass". The former is higher than desirable in a good amplifier, but the latter is very close indeed to the figure of 6 db positive feedback usually permitted in good design (e.g., R.D.H. p. 359). The amplifier is absolutely stable under all possible conditions of load, using transformer A or C. It seems safe to say that it will be absolutely stable with any conventional transformer, or one with the secondary wound in two sections.

Testing with square waves.

For accurate testing with square waves it is necessary to have both a good square wave generator and an oscilloscope with an exceptionally good vertical amplifier — i.e., rapid uptake with no overshoot. These points will be covered in a subsequent article.

One special difficulty which was encountered in carrying out testing on this amplifier was that the setting of the input potentiometer used for the tests had a marked effect on the overshoot. It was found that when the arm was close to either limit (grid or earth) the overshoot due to the amplifier was a minimum, while when the arm was in the mid-position the overshoot was a maximum. Since this particular amplifier was intended for use with a crystal pickup with a load resistance of about 0.5 megohm, it was decided to adopt the worst possible condition with the square wave applied across a potentiometer of this value, set to the mid-point, since this would not be far from the normal operating condition. The cause of this phenomenon is apparently due, at least in part, to capacitances between the terminals of the potentiometer, since a very small capacitance (1 or 2 $\mu\mu$F) had a noticeable effect on the overshoot when connected between input terminal and grid.

Results obtained by tracing the square wave response with resistive load at several different frequencies are shown in Fig. 6. The 50 c/s response (A) is surprisingly good for an amplifier of this class. The 1000 c/s response in (B) and (C) shows very slight difference between these two different transformers. The 5000 c/s response for two different transformers is shown in (D) and (E); the former is slightly overdamped while the latter shows a continued oscillation.

Similar tests on a loudspeaker load at 5000 c/s are shown in Fig. 7. Curves A and B show the waveform with the tweeter disconnected and connected respectively, using transformer A. The results with transformer C were very similar, but the oscillation was somewhat less. Curves C and D show the effect of the RC network shunted across the transformer primary, with transformers A and C, on

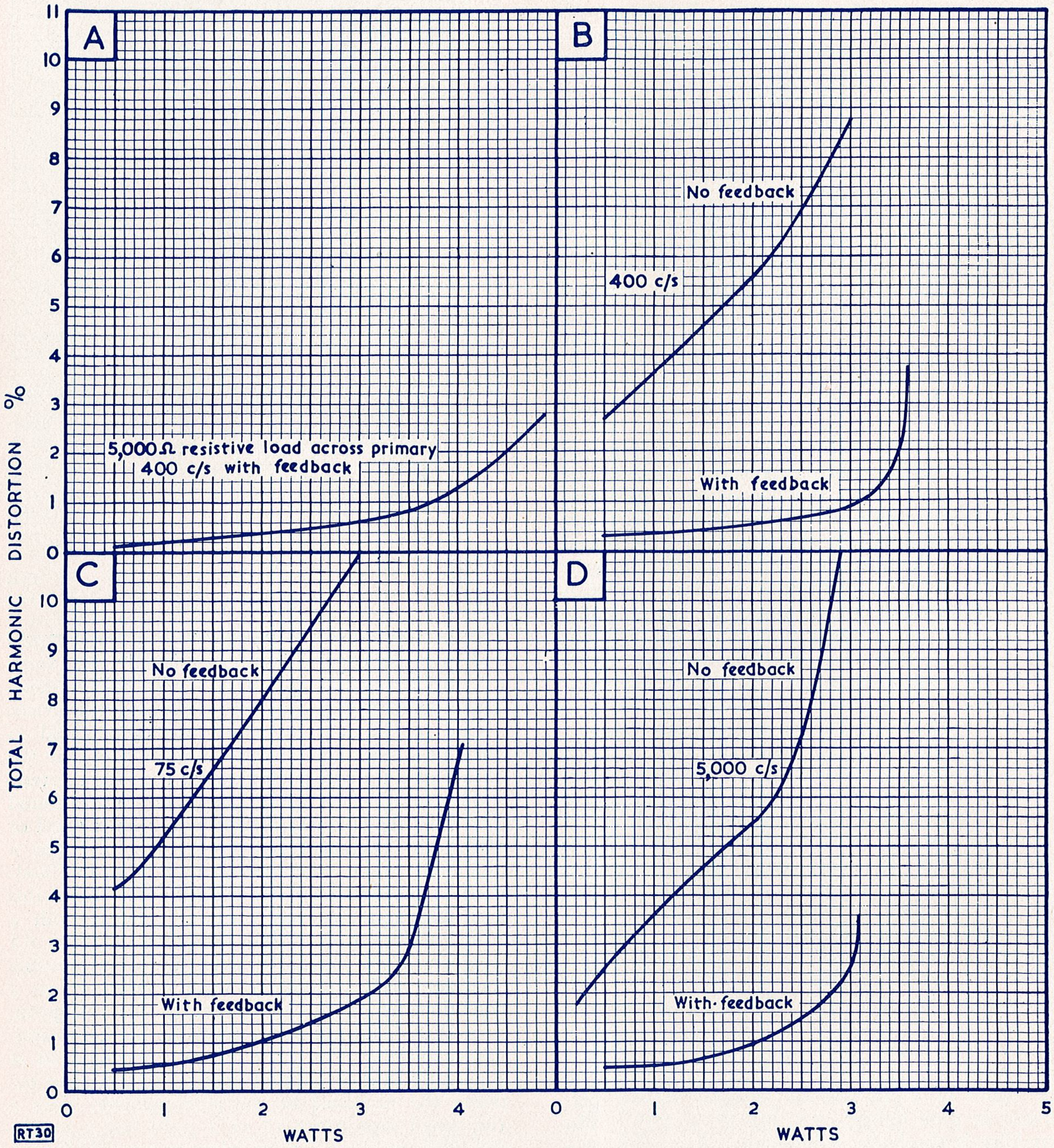


Fig. 3. Total harmonic distortion versus power output using transformer C; (A) Resistive load across primary, 400 c/s; (B), (C) and (D) Resistive load across secondary at 400, 75 and 5000 c/s respectively. [RT30.]

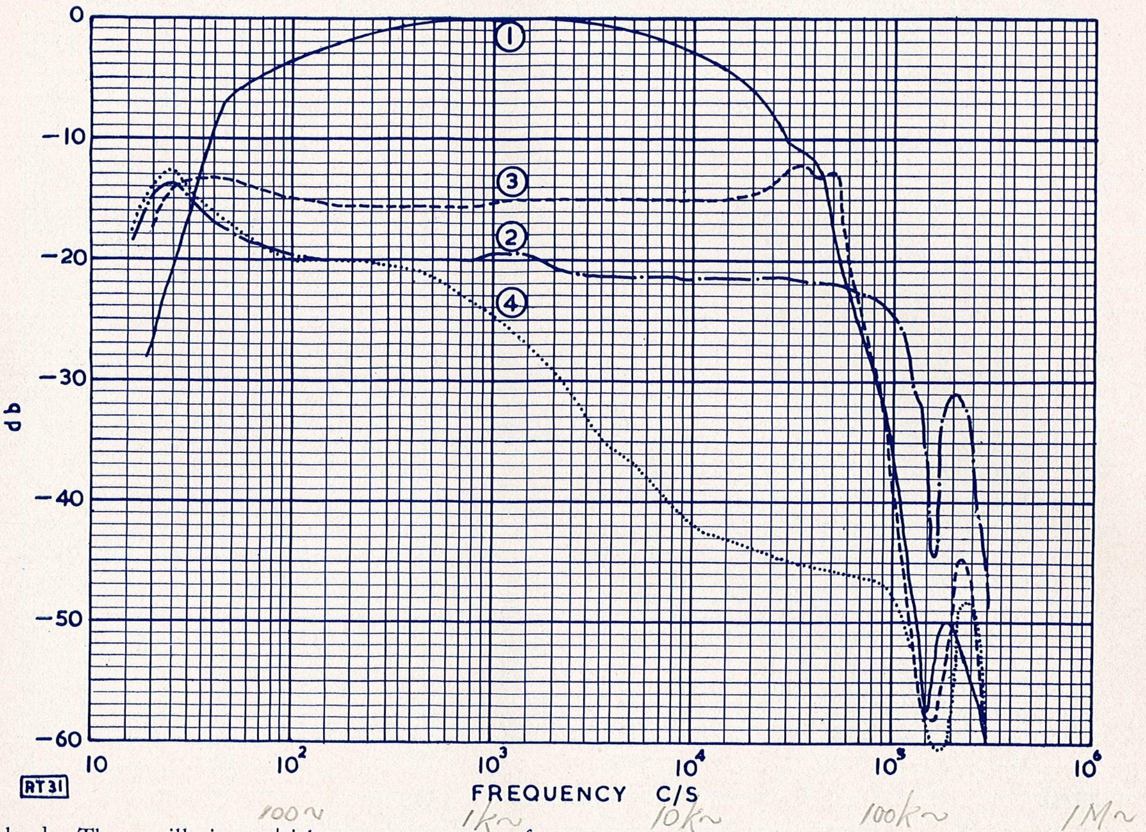


Fig. 4. Frequency response characteristics on loudspeaker load, using 12 inch speaker without tweeter. Transformer C. Curve (1) no feedback, (2) with feedback, tone control flat, (3) with secondary feedback only, (4) with normal feedback, tone control bass. [RT31.]

overload. The oscillation which occurs on one of the peaks is completely eliminated by the network; this effect only occurs on overload, and the network was incorporated principally to give a clean overload, although it also aids the general stability of the amplifier.

Input Circuit.

The amplifier is designed for operation from a crystal pickup, and it has sufficient sensitivity to work from all the crystal pickups on the market with the exception of the Ronette Professional Model TO-284-P which, incidentally, is a particularly good pickup. The latter will not quite give enough output to overload the output valve on LP, and it is recommended that the 3900 ohm feedback resistor be increased to 5600 ohms for this application.

The pickup manufacturer's recommendations should normally be followed in the equalizer network. Pickups which are advertised as requiring no equalizing cannot be correct for both 78's and LP—if correct for LP, they need equalizing on 78's.

The amplifier may also, of course, be used with any magnetic or moving coil pickup followed by a pre-amplifier and equalizer.

Transformers.

A. Manufacturer's Special Products TX1, 5000/12.5. This is a conventional type, with no special precautions to reduce leakage inductance.

B. This has the primary wound in two sections to reduce leakage inductance, being a design specially prepared for these tests.

C. F. G. Apthorpe, of 53 Gardere Avenue, Harbord. Type A10. Secondary wound in two sections to reduce leakage inductance. Special design for this application.

Tabulated Performance.

		THD 1%	THD 2%
Power output—primary	400 c/s	3.7	4.5 W
secondary	400 c/s	3.1	3.5 W
Transformer efficiency	400 c/s	about 80%	

Input voltage for 3.1 watts in secondary 0.35 V r.m.s.
Gain of amplifier at 1000 c/s without feedback
= 170 times = 44.5 db
(from input terminals to secondary)
Gain of amplifier at 1000 c/s with feedback
= 17.3 times = 24.7 db
Gain reduction by feedback at 1000 c/s 19.8 db
Reduction in total harmonic distortion due to feedback at 400 c/s 19.7 db
Attenuation at 10,000 c/s (tone control bass) 20.5 db
Attenuation at 15,000 c/s (tone control bass) 21.5 db
Hum—0.008 volt across 12.5 ohms.
58 db below 3 watts.

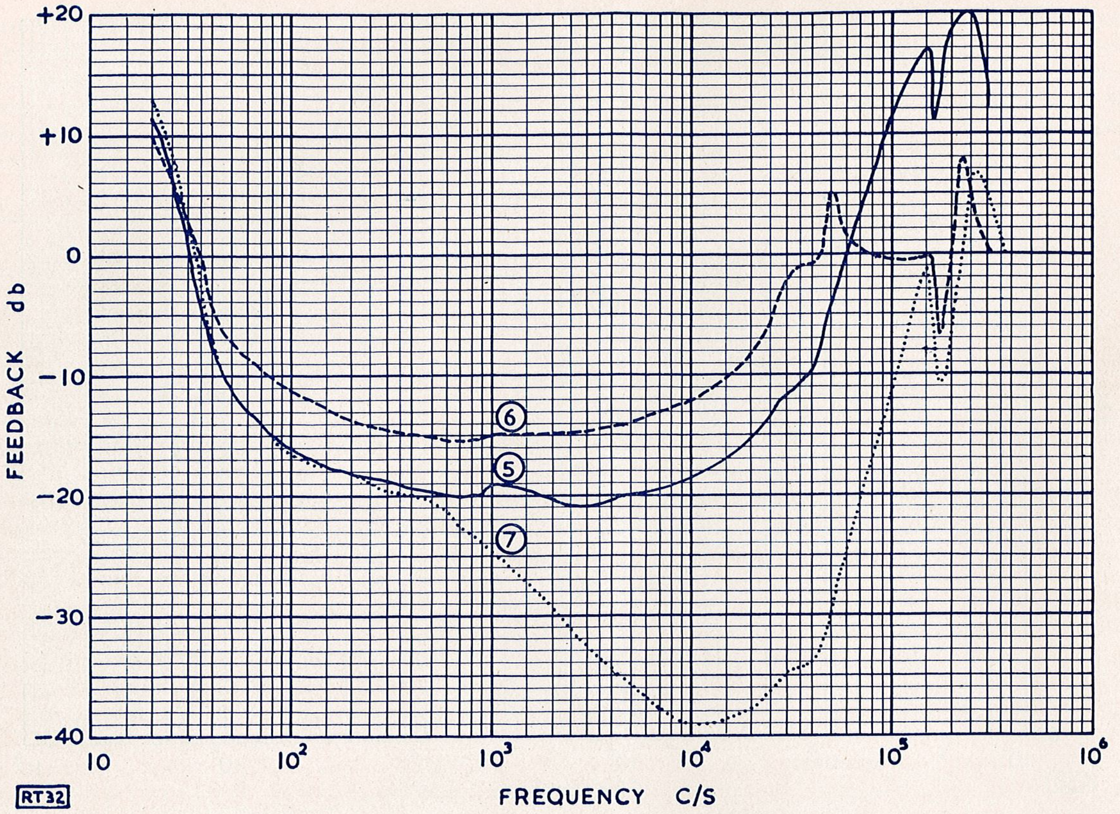


Fig. 5. *Feedback versus frequency characteristics under the same conditions as in Fig. 4. Curve (5) tone control flat, (6) feedback from secondary only, (7) with normal feed back, tone control bass.* [RT32.]

FIG. 6 RT33

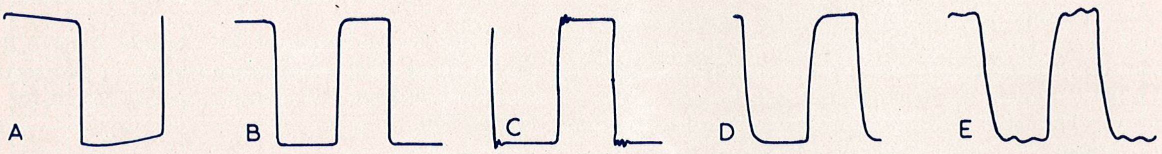


FIG. 7 RT34

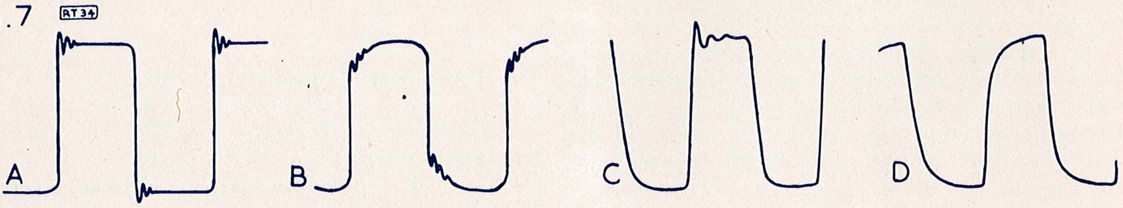


Fig. 6. Square wave response with tone control "flat", on resistive load (A) 50 c/s, transformer B; (B) 1000 c/s, transformer C; (C) 1000 c/s, transformer B; (D) 5000 c/s, transformer C; (E) 5000 c/s, transformer B. [RT33.]

Fig. 7. Square wave response with tone control "flat" on loudspeaker load at 5000 c/s (A) Transformer A with 12in. speaker load; (B) Transformer A with both 12in. speaker and tweeter load; (C) Transformers A and C on overload, without load network shunted across primary; (D) with load network shunted across primary. [RT34.]

TECHNICAL EDUCATIONAL REQUIREMENTS OF THE MODERN RADIO INDUSTRY

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Up to the past decade a course in radio servicing was intended to give the student a working knowledge of operation and maintenance of broadcast and short wave receivers. Such courses covered the circuit refinements employed in receivers of that day. The all-electric receiver had such features as single tuning control, automatic volume control, or delayed automatic volume control, wide response or, in some cases, variable band width intermediate-frequency amplifiers and band-changing switches.

Training courses covered these points by teaching the operation and adjustment of such circuits, giving practice in tracking and alignment of the receiver circuits as well as in checking signal sensitivity and power output. Available commercial testing and servicing equipment permitted the trainees to service the receivers using standardised procedure. Receivers having all of the existing refinments were in the numerical minority and the typical servicing task was handled with facility upon completion of such a course of training.

Requirements Advanced

The appearance of commercial frequency modulation and television broadcasting has introduced servicing techniques of more advanced nature. Receivers for these services operate upon principles which in many respects were not formerly employed. Tracking and alignment procedure must be taught in greater detail to prepare students for the more critical adjustments necessary. Sweep frequency oscillators are now used more extensively than before, and their functions and use must be included in a course of training. Square-wave testing devices are now commercially used in servicing procedure. The latter two pieces of equipment provide means for checking rapidly the characteristics of frequency-modulation receivers and especially of television receivers where the wide frequency response is a prerequisite to good receiver performance.

The additional theory required for this work should be based upon the performance at higher frequencies of the circuits found in such equipment, with emphasis upon the features which have been introduced as a result of the functional changes in the receiver parts. The associated laboratory practice should provide an opportunity for learning the use of such equipment. The interpretation of the results obtained in the laboratory projects must be correlated with the theory.

Practice Essential

The modern course in radio servicing and repair should recognise the value of early opportunity to acquire manipulative skill and familiarity with the tools and equipment of the trade. For this reason beginners in such a course profit by practice work in assembly and wiring while acquiring their basic theory. Laboratory work should continue throughout the course, advancing in level with the theory lessons. As a result of the need for the servicing of the new types of receivers, today's course of training must necessarily be more extensive in total time than were the earlier courses with the lesser objectives.

Students training for employment as radio operators are now required to pass more comprehensive examinations than formerly in order to become licensed operators. In keeping with this requirement it is necessary that a course of study cover receivers more thoroughly and include more extensive study and practice on transmitters. The highly-refined communication receiver of today with its wide range of useful frequencies and the available crystal-controlled tuned circuits calls for skill and understanding in its maintenance.

Transmitters have become more compact and some of the service frequencies are now much higher. Whether the graduate is employed in marine, airline or broadcast stations he finds today's equipment of more complex design than formerly. The scope of training on basic transmitter principles must now be augmented to include more thorough understanding of power amplifiers at radio frequencies, of neutralisation and of the special problems introduced by operating in the higher frequency bands, both with continuous wave and modulated wave transmission. Oscillator theory and performance must be more intensively treated. More time should be allotted to breadboard practice with oscillators and other fundamental circuits which are component parts of transmitters.

As in the case of receiver repair courses, students should find early opportunity in the course to acquire manipulative skills. Additional work on the directivity of antenna structures for special service in the higher frequency range becomes a useful part of the training, especially in connection with such equipment as is used by the airlines for guide beams and landing beams. Marine equipment for safety at sea makes use of the circuit refinements of receivers in the design of the automatic alarm receiver, and in direction finders. The maintenance of radio equipment on shipboard today requires a complete course of training as a technician.

In courses which lead toward higher objectives in technology the student is preparing to fill a position in research and development or in production work. His success and prospect for more responsible work are determined by the thoroughness and completeness with which he is trained in fundamental principles and brought upward through the steps of an organised training programme.

As an approach toward training in the analysis of radio circuits it is necessary to introduce electrical theory, starting with simple concepts of direct

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currents. Mesh circuits should be introduced in their simpler forms, and magnetic circuits should be covered thoroughly. Alternating-current courses should be carefully designed for application to steady-state problems, with applications to the radio field shown as the course progresses. Methods of transforming circuits should be introduced, and the simpler network theorems taught. When the student has acquired this understanding of alternating current circuits he should be given the more advanced work in networks and filters.

Co-ordination a "Must"

His mathematics courses should by this time have reached a sufficiently advanced stage so that he is able to solve transient problems in connection with these networks. The latter study is becoming more significant as a result of the numerous electronic devices which have become common in the war years and the post-war period. Television and radar equipment depend for their successful operation upon circuits designed to accommodate complex wave shapes and signal impulses whose timing and wave form are critical. At a later point in the course the student should have an opportunity to learn the methods of transient solution with the aid of operational methods. It is important that this work be accompanied by co-ordinated training in laboratory procedure, so that the student may improve his ability in checking analytical work with experimental procedure. In this manner he becomes competent in measurements and learns the limitations of measuring equipment.

The square-wave excitation method commonly used today in determining circuit response yields more information than the former laborious method. The interpretation of these results calls for more intensive courses in testing procedure and analysis.

The study of the vacuum tube and its associated circuits must today be carried into the field of microwaves. The relation between internal structure and high frequency performance is important in the electronic devices used in television relay equipment, and in other high frequency apparatus. Communication frequencies today are commercially successful in the microwave bands and the gap between these frequencies and the quasi-optical frequencies is becoming continually narrower. Electron tubes of all types must be treated as a part of the course. Industrial electronic equipment makes use of a wide variety of the newer types of electron tubes. Cathode-ray tubes should be carefully studied, and the analysis of their operation given in considerable detail.

VHF and Composite Signals

In the courses on transmitters and receivers it becomes necessary to include the higher frequencies and the wider frequency response. Pulse transmission and composite television signal transmission call for apparatus which must be designed with a full understanding of circuit and component performance, and this understanding can come only from the analytical methods mentioned earlier. Recent improvements in both the picture signal and the associated sound of commercial television programmes are the result of refinements which are the fruit of experience and engineering skill.

The student well-schooled in the basic principles and whose skill has been developed by laboratory practice should, upon graduation, be able to enter the communications field and handle assignments on modern electronic devices in the field of radio or any of the related subjects such as navigational aids, electronic equipment for diagnosis and treatment in the medical field, industrial heating apparatus, and location and detection equipment. In order that he can be employed in any or all of the above applications his training must be of a broad scope. Navigational aids and detection equipment require training in the high frequencies and in the use of accurately timed pulses of transmission and critically adjusted circuits together with exacting design of antennas. Employment in industrial heating tasks makes demands upon his schooling in the field of high power at radio frequencies and his knowledge of dielectrics. In the medical field his understanding of very low and very high frequency phenomena will be of importance, and his ability to analyse complex wave shapes will depend upon his competence in the mathematical analysis of these shapes. This again emphasises the need for an adequate level of training in mathematics and its correlation with the electrical theory.

Today's heavy demand for educational facilities coincides with the need for the expanded scope of courses as indicated above. The expansion of opportunity for employment in all the levels of training mentioned leads to an increased number of opportunities for technically trained personnel to aid in producing the numerous newly-developed electronic devices which will become commonplace parts of modern industry. To bring these requirement together under a co-ordinated plan of training, the technical school of today must give continuous attention to the modern trends. Course organisation must often be revised with a view to pointing always toward specific job objectives.

Editor .. .. D. Cunliffe-Jones

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