NON-LINEAR
VACUUM-TUBE TOPICS

SOME NON-LINEAR

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By C.B. Fisher, B.A.Sc. (Tor.)

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1. PREFACE

1.1 Abstract

A number of separate circuit problems in radio engineering are discussed, the problems being linked by the fact that they all involve non-linear impedance relations in vacuum tubes. There is also a general discussion given on non-linearity, and a critical bibliography. Among the topics discussed are: automatic volume control in radio receivers; some original work leading to a vacuum tube wattmeter; original analysis dealing with a heterodyne detector; a constant impedance circuit primarily intended to meet the problems of coupling a pentode tube to a loud-speaker; and some original work on an amplifier involving de-generation to meet the same problem. A number of measurements are shown to back up the discussion on each topic.

1.2 Significance of Results

In order to allow the general reader to obtain an idea of the importance of the results obtained, this sub-section will review these results briefly. Section 2 contains nothing new, but may be of some value as bringing together for a common consideration these non-linear phenomena which are usually handled separately. Section 3 on automatic volume control contains no new material except for sub-section 3.9 which deals with an original idea which may have considerable merit. The main part of the section is merely a text-book discussion of the topic, which has not previously been given. A small point, perhaps, is the introduction of the "load curve", which had not previously been published, and which has already been adopted by one or two writers. The whole section is the outcome of the design by the writer of several commercial radio receivers employing automatic volume control. In section 4 the new idea of a vacuum tube wattmeter is considered, and while the results obtained are of more interest than value, still it is thought that further development may result in an entirely workable instrument. Section 5 on the heterodyne detector presents results which are of little importance, and are included here mainly for their interest. The constant-impedance coupling circuit dealt with in section 6 is very simple in theory but does not appear to have been used up to the present time, and may be of some importance. The use of de-generation in certain amplifiers is dealt with in section 7, and it was not until the study of this topic was completed that a search revealed a patent covering the fundamental circuit. The circuit and its variations appear to deserve a greater application than they have found.

1.3 Previous Publication of Results

The section on automatic volume control was published in practically its present form in the "Wireless Engineer", May, 1933. Sub-section 3.(10) has been accepted for publication by "Radio Engineering" and the material of section 3 on the heterodyne detector has been accepted by the "Wireless Engineer".

1.4 Acknowledgment of Assistance

The assistance is gratefully acknowledged of Professor Christie and Dr. Howes of McGill University under whose direction the work was carried on, and of Mr. H.J. Vennes through whose kindness it was possible to carry on the experimental work in the laboratories of the Northern Electric Co., Ltd. at Montreal.

1.5 Apologia

It is felt that some explanation is required of the apparently unrelated topics which form this thesis. Originally the thesis was intended to deal only with automatic volume control, but when this subject had been carried as far as it seemed profitable to take the study, it was felt that a number of other topics which frequently cropped up could well be handled under the ruling genus of non-linearity. There has been no attempt to study non-linearity. Rather the plan has been to study a number of related topics which involved this feature. It is felt that in carrying out this scheme a number of questions have been brought up which point the way to a further fruitful study, and in this way the basic plan has been justified. This thesis presents the results of work done intermittently as private studies and as part of a program of development by the Northern Electric Company.

It is also thought that something should be said as to the method of presentation. No attempt has been made to present elementary facts; for example, no reference has been made to the definition of the decibel. The material has been handled as if it were intended for the technical press.

2. GENERAL

2.1 Importance of Subject

The general topic of non-linear circuit elements in electrical networks covers a field of tremendous importance. We can briefly pass over the effect of such elements causing harmonic generation in power generators and transformers, and consider apparatus where such non-linear elements are purposely introduced. The most important of these are circuits where the non-linear element is introduced by an electronic vacuum tube.

For the most part these circuits are concerned with modulation and de-modulation in radio or wired telephone carrier systems. This is the greatest field of the non-linear vacuum tube, and was originally the only use of the vacuum tube. In the last few years vacuum tubes have been used as non-linear elements in a wider variety of circuits. Rectifiers, automatic volume control, power relay control, noise-suppression circuits, and many others, have all utilized the vacuum tube's versatility in this direction. There have also been developed the newer circuits where the non-linear aspect of the tube is of importance, but less welcome. These include the circuits using pentodes, screen-grid tubes, class B and class C amplifiers.

2.2 Historical Outline

This subject of vacuum tubes might be said as yet to have almost no history, as the original model, the 2-element valve, was patented as a wireless receiving device by Fleming only in 1904. The Edison effect on which this device was based had been known for some years.

Fleming's valve was used principally as a detector of damped radio waves, replacing to a small extent the crystal detectors then in general use. The Fleming valve showed considerably greater stability, but its cost and short life made its application small. The action of the valve was thoroughly understood, so that the earliest vacuum tube was in good standing as a non-linear device.

In 1906 Lee de Forest brought out his "audion", which was a Fleming valve with a third control electrode added. This device is the direct progenitor of the modern vacuum tube. De Forest's tube at once gained acceptance as a detector of high sensitivity, but the non-linear action was imperfectly understood, and as late as 1918 commonly used text-books contained serious errors relative to its detecting properties. Thus, for example, we find circuits of detectors with grid condensers, but no grid leaks. Throughout this period the commercial tubes suffered from low internal pressures, which gave irregular operation, thus rendering an analysis of their functioning difficult.

In 1916 O.W. Richardson had completed his monumental researches on the electronic emission of a heated electrode in a vacuum, and shortly afterwards the vacuum tube was functioning as a modulator in the transatlantic telephone circuit. Van der Bijl and his associates in the Bell System were largely responsible for perfecting modulation devices and making a complete theoretical study of the vacuum tube, so that by 1918 when van der Bijl's book, "The Thermionic Vacuum Tube", appeared, the fundamental knowledge of these devices was practically at its present position. Since then there has been an immense refinement in design of vacuum tubes, and their applications to new circuits.

2.4 Discussion of Non-Linearity

In electrical networks, non-linear circuit elements may be defined as elements which do not obey Ohm's law. That is, the instantaneous current flowing through the element is not strictly proportional to the voltage across the element.

Mathematically, then, the question of non-linearity is in essence extremely simple and has been well understood for several centuries. When, however, the argument of a non-linear function is written as a sine function of another variable, rather interesting results are obtained. The sine wave of current, it has been pointed out, is the only wave form which can be transmitted through any linear passive network without change in form. In contrast, the non-linear network will change the shape of even a sine wave, and in this property lies its whole value in circuit design. This property of the non-linear element gives rise to two separate groups of phenomena.

If, first, a single sine function is written as the argument of a non-linear function, the function can readily be broken down into a number of sine terms having harmonic relationships with the original sine wave. There will also appear terms not involving the variable. This property of the non-linear function makes possible circuits for rectification, automatic volume control, frequency multiplication and many other uses.

In some cases, however, we may write the sum of two or more sine waves as the argument of the non-linear function. If now the function in broken down into terms of unity power, there is found a group of sine functions having variables equal to the sums and differences of various integral multiples of the original variables. This property brings about all the modulation and demodulation phenomena, the vacuum tube wattmeter, and the superheterodyne receiver.

In electrical circuits the non-linear element is often, though not always, supplied by a vacuum tube. As examples of other devices, consider the aluminum electrolytic rectifier, the crystal detector, and more particularly the copper-oxide rectifier, and the thyrite lightning arrester.[1]

Vacuum tubes are especially valuable as non-linear elements, because non-linearity may occur in three ways. First, the grid-voltage grid-current curve is usually discontinuous near the origin, and for negative values of grid voltage, no grid current flows. This property is widely used in grid-current or

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(1) Thyrite - a dense homogeneous inorganic compound of a ceramic nature perfectly stable, and mechanically strong. This new material possesses the remarkable characteristic of being substantially an insulator at one voltage and becoming an excellent conductor at a higher voltage. The electrical resistance of thyrite is a function of voltage only, the resistance decreasing and the current increasing 12.6 times each time the voltage is doubled. (Ref. 17)

van der Bijl modulators, the grid detector, and in certain control circuits.

Furthermore, the plate current is not a linear function of plate voltage, but obeys in some cases a three-halves power law. This property is used to advantage principally in the Heising or plate modulation circuit.

The vacuum tube also has the property that the mutual characteristic may not be linear. That is, the plate current is not a linear function of grid voltage. This effect is used as the basis of the plate detector, the grid-bias modulator, and in some control circuits.

3. AUTOMATIC VOLUME CONTROL FOR RADIO RECEIVERS

3.1 Abstract

The value of automatic volume control for radio receivers is discussed, with a description of the developments up to the present time. Details of a typical circuit are given, and the curves of its operation are shown. Various limitations on the circuit are considered.

3.2 Introduction

Automatic volume control, (or A.V.C. as it is commonly abbreviated) is a phrase used to describe the operation of a circuit in a radio receiver, so that signals are always heard with substantially the same loudness, irrespective of the signal strength received from the transmitting station. A more correct phrase would be automatic gain control. That is, once the listener has adjusted his receiver to give him the desired volume, changes in signal strength due to fading cannot be detected by changing loudness, unless the signal strength drops below some minimum volume which will depend on the particular receiver.

Receivers incorporating automatic volume control have been on the Canadian and American markets for some years and at the present time there is almost no model of any pretensions which does not include an automatic volume control circuit. As the advantages become more generally apparent to the buying public and as competition between manufacturers becomes keener due to sales saturation and to further advances in design and production, it may be expected that receivers in even the lowest price classes will include circuits which will attain automatic control.

3.3 Usefulness of A.V.C.

When receivers using automatic volume control circuits first appeared the idea met considerable opposition among engineers. This opposition has for the most part disappeared, as it is now generally realized that advantages are gained which are not immediately apparent, and as more suitable designs are now available.[1]

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(1) W.T. Cocking in an article in "Wireless World", August 12, 1932 p. 116, states that no British receiver includes an A.V.C. circuit and points out that the British radio engineer is not yet convinced of the value of such a circuit. The present writer cannot find himself in agreement with Mr. Cocking's conclusions as to the value of A.V.C. and suggests that anyone desirous of forming an opinion on the subject should provide himself with a really first-rate receiver equipped with A.V.C. and make wide use of it for several weeks. As Mr. Cocking says, "This is by no means a technical matter; it is more a psychological point upon which both the technical and non-technical are equally competent to judge." Our experience has been that when an acute, but non-technical listener has used a receiver with an A.V.C. circuit, he will never willingly return to one not so equipped. In cases of automobile receivers, and receivers operating on commercial point-to-point circuits subject to fading, there can of course be no question of the value of A.V.C.

The most obvious use of A.V.C. is to minimize the effect of atmospheric fading of signals. Until the signal has faded below the noise level, or below the limiting value which can be handled by the receiver, the output level from the speaker will remain dependent only on the original modulation. This feature is particularly valuable in the case of a highly sensitive receiver which will be used frequently on distant stations, whose signals are particularly subject to fading. Experience has shown that transmissions of medium frequencies (500 KC to 1500KC) will often undergo amplitude variations of 40 db. or more with comparatively little modulation distortion. Where fading is more severe, it is usually accompanied by some modulation distortion, so that an anti-fading device cannot restore to the signal its pristine quality. However, the reception will be more satisfactory than if the anti-fading circuit were inoperative.

In well-designed commercial receivers it has been found easily possible to secure receiver output variations not greater than 6 to 10 db. with carrier input variations of 80 db. or more, say from 10 microvolts to 100,000 microvolts. In fact, with many of the receivers on the American market, the listener will cease to listen to a station not because the signal fades to inaudibility, but because while the signal output is satisfactory, the noise level may become objectional at periods of extreme fading.

A similar application of A.V.C. circuits which has recently become important is their use in automobile radio receivers, both for police patrol and for entertainment purposes. Here the rapidly changing location results in very sudden and severe "fading", rendering manual volume control nearly impossible. At frequencies near 1000 KC it is not unusual to find in city streets within a few miles of the radio transmitter, variations of field strength of some 40 db., say from 100 microvolts to 10,000 microvolts per meter, in the space of a few feet, representing a time of less than a second for a moving car. This condition becomes more severe as the frequency is raised, and as frequencies assigned for police work in the American cities lie as high as 2450 KC the problem is of special interest. Further factors in police work which necessitate A.V.C. circuits are the low power available for transmission (500 watts maximum unmodulated antenna carrier power) and the operation of the patrol cars in solidly built-up districts, where radio "shadows" are more marked. It is also extremely undesirable for the patrol cars to lose touch with the transmission for even short periods, so that the receiver performance requirements are quite rigid. Police transmissions are usually deeply modulated in order to make the most use of the limited power available, and also a high degree of intelligibility is required. Both of these factors render difficult the design of the A.V.C. circuits, as will be discussed in detail below.

Another advantage of a receiver equipped with A.V.C. is that there is prevented the terrific din that results when a careless user is exploring the broadcast band for distant stations, and suddenly tunes across a powerful local transmitter. With receivers in common use capable of delivering amounts of power of the order of 10 watts to the loudspeaker, some such safety device becomes imperative.

The remaining advantages which we shall discuss here are entirely angles seen from the viewpoint of the design engineer. The first has to do with detector performance. The modern linear detector requires for best operation that the input voltage should be between somewhat close limits, the upper limit being set by the commencement of grid current, the lower limit occurring at the point where the detection diagram departs sensibly from linearity. The A.V.C. circuit holds the input voltage well within limits, so that a condition of nearly ideal detection can be attained.

The other distinct advantage of A.V.C, from the designer's point of view is that it provides a second gain control for the receiver. When we consider that the modern high-gain receiver must handle input voltages of from say 10 microvolts to 200,000 microvolts, and must deliver at the will of the operator an output level of from 10 milliwatts or less up to 10,000 milliwatts or more, the volume control problem becomes immediately apparent. The above limits correspond to a change in voltage amplification of roughly a million to one, or 120 db. With manual volume control the attenuation is generally introduced ahead of the detector, often as combined control of input voltage, and regulation of tube gain, in order to secure sufficiently great variation in overall amplification. In a receiver employing A.V.C. on the other hand, the A.V.C. circuit takes care of changes in gain made necessary by different input voltages, and a manual volume control is introduced into the circuit subsequent to the detector, and by this means the output level from the receiver is adjusted to the desired value. Thus the variation in gain is divided between the radio-frequency and audio-frequency amplifiers with the result of better detector performance as has been seen, better radio-frequency amplifier characteristics, as will be seen later, and finally minimization of microphonic or other noise introduced by the detector or other parts of the audio-frequency circuits ahead of the manual volume control. For at low output volumes with moderate signal strength extraneous noises are attenuated by the manual volume control in the same ratio as the music or speech, and only reach their maximum when the audio amplifier is operating at full gain. Such an advantage might be gained to a limited degree even in a receiver not incorporating an A.V.C. circuit by providing a second gain control, in the audio-frequency amplifier, and ganging it with the conventional radio-frequency control. This problem is discussed in more detail in a subsequent section.

3.4 Requirements for an A.V.C. Circuit

The principal requirement of an A.V.C. circuit is that the operation of the control circuit should depend only on the strength of the incoming carrier, i.e., the control should be independent of modulation. Only if this is true can the receiver output faithfully follow every change in amplitude of the original sounds producing modulation of the transmitted carrier.

For the control to be of utility the A.V.C. circuit must hold the output level within quite close limits, say 6 to 12 db., for wide variations in incoming carrier voltages, say 60 to 80 db., the depth of modulation remaining constant.

This point brings up the further consideration that the A.V.C. circuit should not operate to reduce the receiver gain until the signal input has reached a value sufficiently high to cause the receiver to deliver nearly its maximum output. Conversely the gain control must be sufficiently effective on signals from powerful local transmitters to prevent overloading of the final r.-f. amplifier tube or detector.

The requirements on the speed of the control action vary widely in the different applications. In automobile receivers it has been found of advantage to provide an A.V.C. circuit which can reduce the gain of the receiver 40 db. in less than one-tenth of a second. For point-to-point receivers on circuits subject to rapid fading the control action may be as slow as half a second for a 40 db. change in gain. In receivers intended for broadcast reception it is becoming usual to find circuits which will operate to reduce the gain quite quickly, but which take several seconds to allow the gain to rise 40 db. This feature is introduced in order to give freedom from noise while tuning quickly from one powerful station to another. Since this is the usual procedure, the listener is not bothered by the background of noise which is heard if the receiver is allowed to rise to its maximum gain immediately it is detuned from the incoming signal. At the same time the period of fading at the broadcast frequencies lying in the neighbourhood of 1000 KC is usually comparatively long and the A.V.C. is able to follow the changing amplitude of the signal.

3.5 Methods of Securing A.V.C.

The most usual A.V.C. circuit is shown in fig. 3.1. The control tube may be either a three- or four-electrode valve, but it is more commonly the latter. The radio-frequency voltage applied to the detector grid is also applied through a blocking condenser to the grid of the control tube. In some circuits the r.-f. voltage is secured at the plate of the last r.-f. amplifier tube. The control tube is biased to a point at or beyond plate-current cut-off. Thus no plate current flows until the r.-f. voltage on the grid has exceeded some predetermined value. At this point, however, due to the non-linear characteristic of the tube, direct current begins to flow in the plate circuit. This current flows through a resistance and the resulting voltage drop is applied as a negative bias through a resistance-capacity filter to the grids of the r.-f. amplifier tube, with a consequent reduction in gain. The circuit quickly settles down to a state of equilibrium.

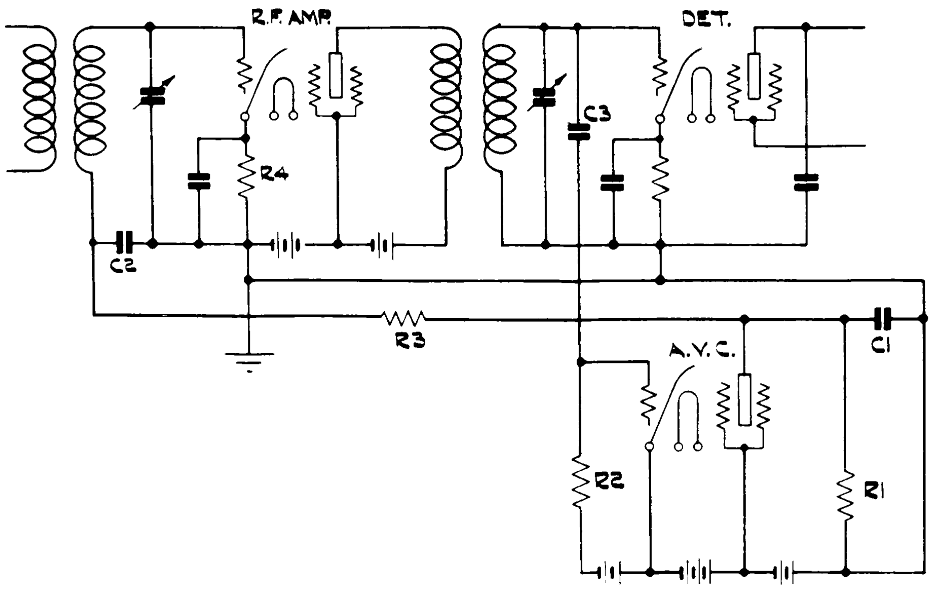


FIG. 3.1
SCHEMATIC DIAGRAM OF A TYPICAL
A.V.C. CIRCUIT

Notice that the total battery voltage necessary is equal to the sum of the r.-f. amplifier plate voltage and minimum grid bias plus the control-tube plate voltage and grid bias. In commercial broadcast-receiver design these values are commonly 180, 1½, 45 and 3 volts, respectively. Common practice has been to use the grid-bias voltage of the audio-output stage also as plate voltage for the control tube. Notice also that the cathode of the control tube is at a potential lower than the cathode of the r.-f. amplifier tubes by an amount roughly equal to the plate voltage on the control tube. This condition militates against the use of filament-type tubes, unless a separate filament-current supply is provided for the control tube. With tubes having indirectly heated cathodes in circuits where the heaters must be connected to a common supply, the plate voltage of the control tube is limited, generally to 45 volts, in order not to break down the insulation between heater and cathode in the control tube. In special applications, however, where sensitivity of control is more important than tube life or economy, plate potentials as high as 135 volts have been used on the control tube.

Several other schemes have been devised to secure A.V.C., such as the use of mechanical relays which are operated by the plate current of the control tube and which switch attenuating networks into the amplifier circuit. Also patents have been taken out on a circuit in which the gain of the r.-f. amplifier is reduced by a change in screen voltage, rather than by a change in grid bias as described above.

Two recent developments that promise to become of considerable importance are the Wunderlich tube, and the duo-diode tube. The Wunderlich tube is designed to operate as a grid-leak detector handling comparatively high input voltages with good modulation characteristics. By a suitable arrangement of the circuit, the d.-c. drop across the grid leak due to the incoming signal is applied as a bias to the grids of the r.-f. amplifier tubes, so that automatic gain control is achieved.

The duo-diode tube can be used in a similar manner to obtain automatic control. As the name implies, the tube includes two diodes, which can also be used, one as a detector and one as a rectifier supplying bias for an A.V.C. circuit.

In this case the two functions are quite separate so that no detection qualities need be sacrificed to secure a satisfactory control action. It is further apparent that even the usual bias detector can be arranged so that the increased plate current due to an incoming signal will cause an increased bias to be applied to the r.-f. amplifier tubes, thus securing a measure of automatic control of gain.

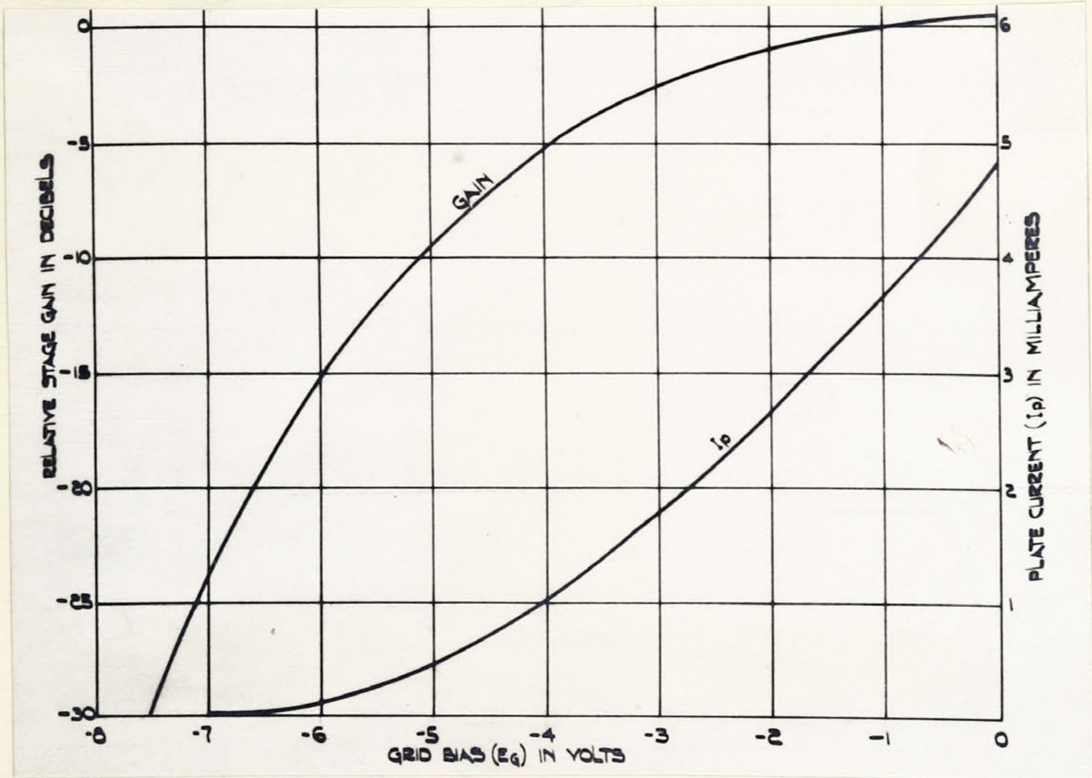
3.6 Performance of Typical Circuit

The following paragraphs under this heading show the results that may be obtained by the most usual type of A.V.C. circuit. While the curves apply exactly only to one circuit using a particular type of tube, nevertheless the performance may be duplicated or surpassed by the use of almost any modern screen-grid valve.

In the circuit of fig. 3.1 the following values of the components are used:

R1	500,000 ohms	C1	0.1 mfd.
R2	1 megohm	C2	0.1 mfd.
R3	100,000 ohms	C3	0.0001 mfd.

The three tubes shown are type '36 , as made by a number of manufacturers in Canada and the United States, and are heater-type screen-grid tubes intended primarily for use in automobile receivers. In fig. 3.2 are shown curves for this tube as an amplifier. That is, plate current (I_p), amplification factor (μ), plate resistance (R_p) and relative gain per stage (G) are shown as functions of grid bias, for a plate voltage of 135 and a screen-grid voltage of 67. The relative gain per stage has been computed on the assumption that the voltage amplification per stage is proportional to the mutual conductance of the tube, and the gain with the minimum grid bias (i.e. the bias due solely to the voltage drop across resistance R_4) has been arbitrarily denoted zero db.



The additional data required deal with the performance of the gain control tube and are shown in fig. 3.3. Curves are shown of plate current against R.M.S. radio-frequency voltage applied to the grid, for a number of values of grid bias.

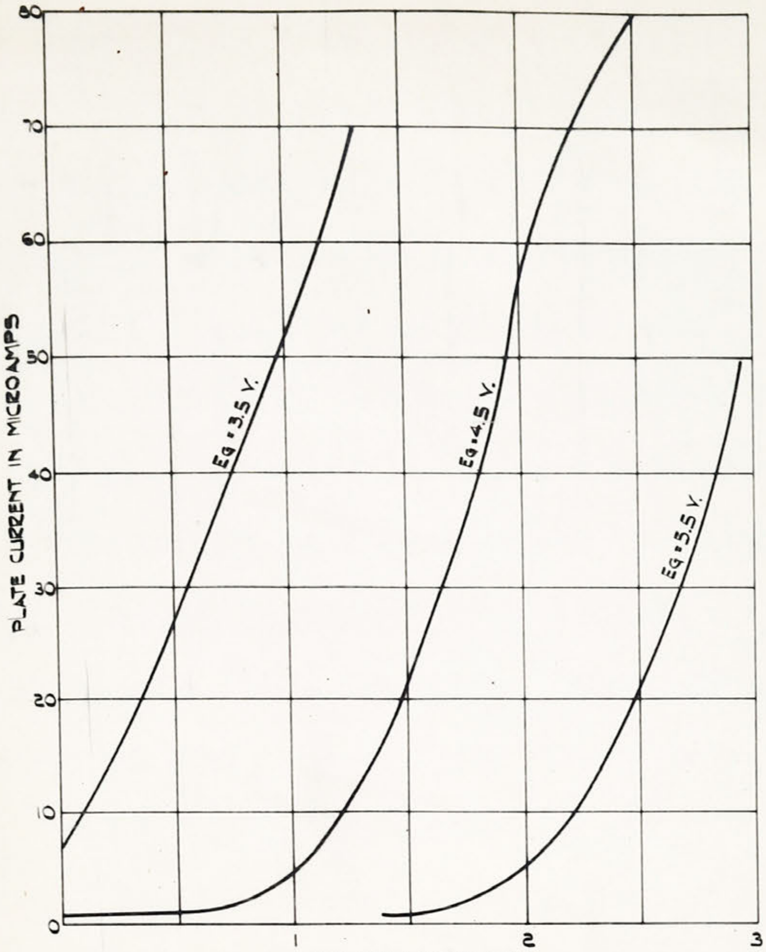


FIG. 3.3
CHARACTERISTICS OF CONTROL TUBE

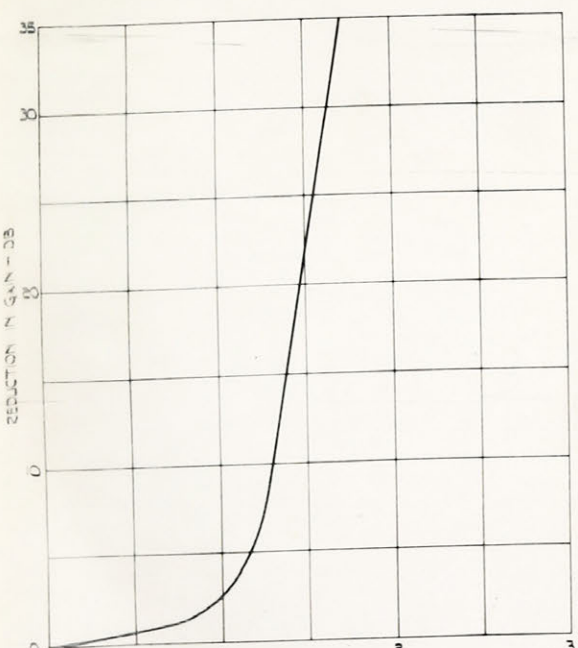


FIG. 3.4
REDUCTION IN GAIN OF ONE AMPLIFIER TUBE DUE TO A.V.C. ACTION

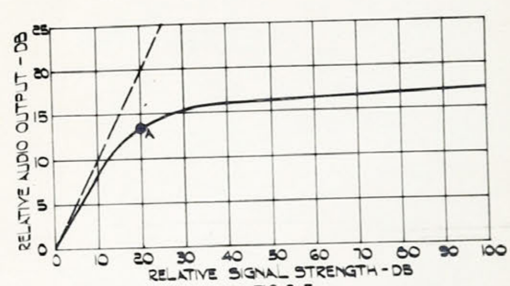


FIG. 3.5
LOAD CURVE OF RECEIVER WITH 3 TYPE 36 TUBES. POINT 'A' CORRESPONDS TO 1.0 VOLT AT DETECTOR GRID.
SOLID LINES SHOW OPERATION WITH A.V.C.
DOTTED LINES SHOW OPERATION WITHOUT A.V.C.

The plate voltage is 45, the screen voltage is 22, and the plate resistor 500,000 ohms in each case. The two latter values were determined to be the most suitable by a series of measurements. For the sake of an example, we make the assumption that the r.-f. voltage on the detector grid is to be allowed to reach 1.0 volt r.m.s. before the control is to act to reduce the gain to any extent. Referring to fig. 3.3 again we see that the curve for $E_g = 3$ volts would meet this condition. We can now readily plot the bias voltage supplied to the r.-f. amplifier against a.-c. voltage on the detector grid. By combining this information with that derived from fig. 3.2 we are enabled to plot the curve of fig. 3.4, which shows the change in gain per stage of the r.-f. amplifier against input voltage to the detector grid. From this curve by an obvious process has been derived the data leading to the curve of fig. 3.5, which has been called the "load curve" of the receiver. This shows the variation of audio-output voltage with the r.-f. input voltage to the receiver, and has been drawn on the basis of three similar r.-f. stages, linear detection, and constant depth of modulation.

We have now secured the desired performance curve of the A.V.C. circuit. The circuit has been seen to act in the desired manner. The r.-f. gain suffers no reduction until the detector voltage rises above .5 volt . At 1.0 volt the reduction is only 7 db. In order to increase the detector voltage 4 db. or to 1.5 volts, it is necessary to increase the signal input to the receiver by 80 db.

3.7 Limitations on A.V.C. Circuits

So far there has been no mention of the difficulties introduced by the operation of the A.V.C. circuit. The first of these is its influence on r.-f. amplifier characteristics. Due to the fact that the gain must be varied over a wide range by a variation in grid bias alone, cross-modulation and rise-in-modulation are apt to occur in the amplifier tubes. Earlier designs for receivers avoid this condition by using "local, long-distance" switches which are intended to introduce attenuation into the antenna circuit when powerful signals are being received, and also by arranging the circuit in order to secure most of the variation in gain in the earlier r.-f. stages, where the signal voltage is low. The variable-mu tube was introduced several years ago mainly to meet the conditions in this circuit, and has solved the problem admirably. These tubes, however, have mutual conductances which in some cases decrease comparatively slowly with increasing grid bias, so that a load curve of as satisfactory a shape as that of fig. 3.5 cannot be obtained in every case. As an example of the use of a variable-mu tube

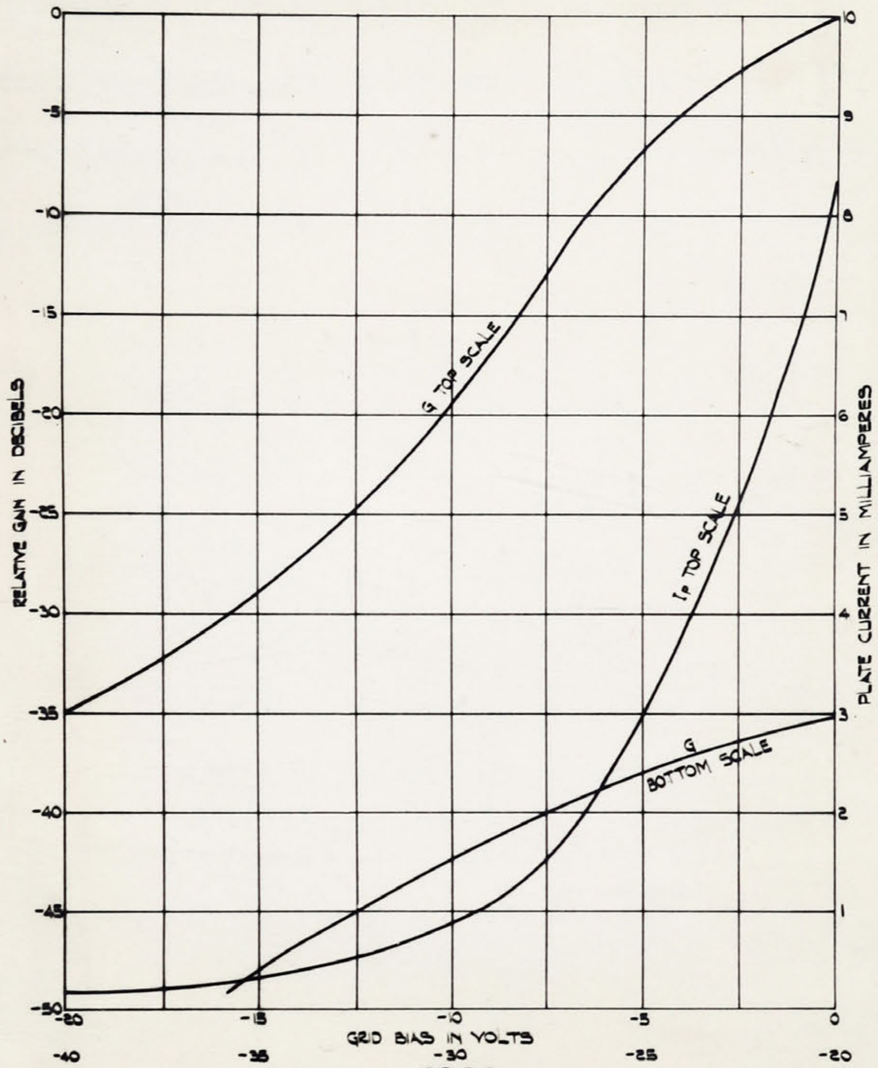


FIG. 3.6
AMPLIFIER CHARACTERISTICS OF AMERICAN TYPE '39 TUBE FOR PLATE VOLTAGE 135, SCREEN VOLTAGE 90.

the curve of plate current and mutual conductance versus grid bias are shown in fig. 3.6 for a type '39 tube. This is a variable-mu r.-f. pentode also designed for automobile use. The corresponding load curve of a receiver employing three of these tubes as r.-f. amplifiers is shown in fig. 3.7. It is seen that a very satisfactory degree of automatic volume control has been achieved.

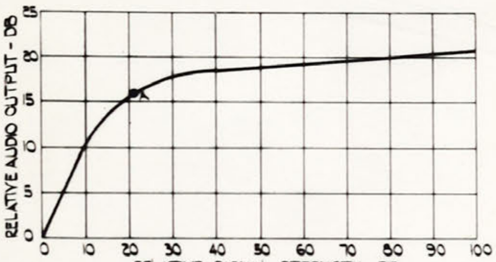


FIG. 3.7
LOAD CURVE OF RECEIVER WITH 3 TYPE '39 TUBES
POINT 'A' CORRESPONDS TO 1.0 VOLT R.F. AT DETECTOR GRID.

The other principal difficulty is the effect on the gain-control circuit of the modulation of the incoming signal. Consider the action of the gain-control tube when an unmodulated carrier of 0.25 volts is being applied to its grid. Fig. 3.3 shows that no plate current flows and the gain of the r.-f. stages is not reduced. If now the carrier is completely modulated at an audio-frequency rate, the voltage on the grid of the control tube will reach 0.5 volts at the peaks of the audio-frequency wave. Plate current will then flow intermittently in the control tube. Audio-frequency components will be severely attenuated before reaching the grids of the amplifier tubes, but the d.-c. component will cause a reduction in gain, which is not desirable.

Two things may be done to minimize this effect. First, the action of the control is made slow by suitably proportioning condensers C1 and C2, and resistance R3 of fig. 3.1. The gain is then reduced by an amount corresponding to the average depth of modulation over a period of time. As this average depth is usually quite small, and changes slowly, the effect of modulation on the gain control circuit becomes less noticeable. The second method of securing improvement is to use circuit values which give curves similar to those of fig. 3.3, but of smaller slope. This change results in a less satisfactory load curve for the receiver, but is generally made in order to secure freedom from modulation distortion.

Another factor which requires consideration in a receiver using A.V.C. is the question of tuning. The effect of the control circuit is of course to make the receiver appear less selective, particularly with powerful signals. In the case of highly selective receivers it is important that the receiver be tuned accurately to the incoming carrier, and to assist in this it is usual for the receiver to include a "tuning meter". This is simply a milliameter connected in the plate circuit of one or more of the r.-f. amplifier tubes. As the A.V.C. circuit acts to reduce the plate current of these tubes, the tuning dial is adjusted to cause the meter to read a minimum value. Other devices are in use, such as a light which is made to glow with the minimum brightness and so on.

3.8 Conclusions re A.V.C.

Automatic volume control may be a cure for some of the evils which beset a radio receiver. It is an extremely inexpensive addition to an existing design, as apart from the provision of one tube, practically nothing but the most inexpensive of components is required in the way of additional apparatus. A receiver designed to include an A.V.C. circuit must of course meet several conditions; it must have a detector designed to receive comparatively high voltages, and the r.-f. amplifiers must be capable of sufficient variation in gain to meet the conditions of signal variation.

3.9 An Improvement in Manual Volume Control

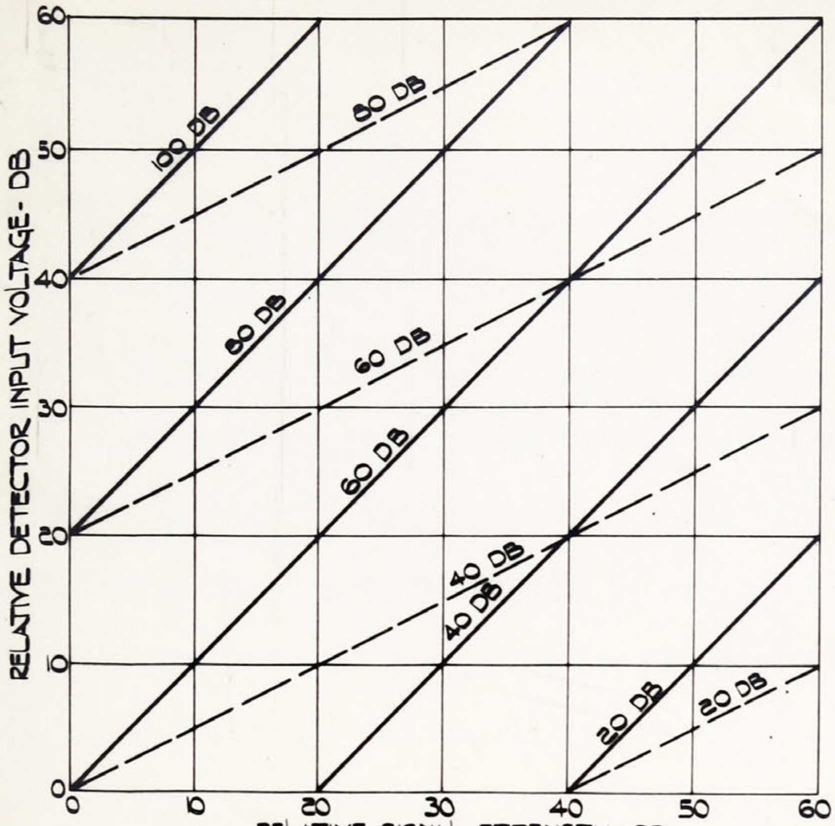
The addition of automatic volume control to a radio receiver results in improvements in several directions. In receivers not so equipped, however, several pressing problems require solution. These are in order of importance.

1. The detector must handle a wide range of input voltage, as the volume control must be placed in the r.-f. amplifier, and the detector input voltage will be proportional to the voltage delivered to the speaker. This means that detection will be far from linear at low output values.

2. The whole desired change in gain must take place in the r.-f. end, resulting when the gain is highly reduced, in cross-modulation and rise in modulation in the r.-f. tubes.

3. The extraneous noise in the output from the receiver due to power-frequency noise introduced by the detector or subsequent circuits, microphonic noise, etc. remains constant although the output level may be widely varied. This means that with very low output levels the noise may be noticeable, or at least extraordinary precautions must be taken to hold it to a satisfactory value.

A partial solution to these problems is found by applying A.V.C. technique to the circuit and consists of providing two volume controls, one in the r.-f. circuits preceding the detector, and one in the audio circuits subsequent to the detector, these two controls then being ganged together and operated by a single knob. It can be shown that under these circumstances for the greater range of signal strengths and output levels the input voltage to the detector will vary between closer limits than was the case before, also since attenuation is placed in the audio end, the necessary change in r.-f. gain is reduced, thus improving operation of the r.-f. amplifier. Extraneous noises introduced in the detector or subsequent circuits are reduced at the same time. The curves of figures 3.8 and 3.9 have been plotted to show the degree of improvement brought about in an actual case. These curves have been plotted from the following data.

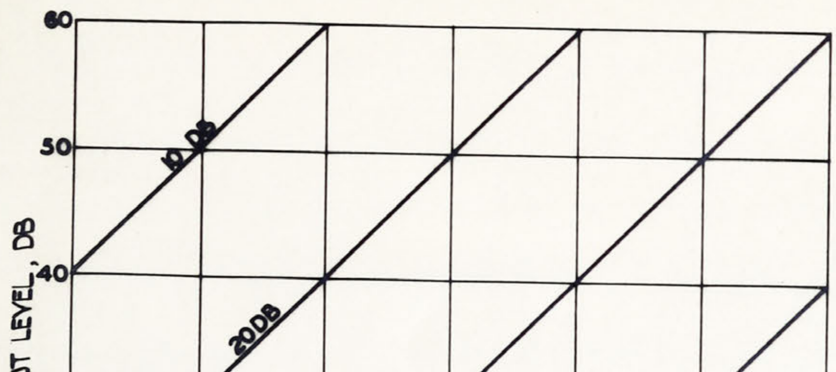


RELATIVE SIGNAL STRENGTH - DB

FIG. 3.8

VARIATION IN DETECTOR INPUT FOR VARIOUS RELATIVE CONSTANT AUDIO OUTPUT LEVELS

SOLID LINES - SINGLE VOLUME CONTROL
BROKEN LINES - DOUBLE VOLUME CONTROL



RELATIVE SIGNAL VOLTAGE, DB

FIG. 3.9

REDUCTION IN AUDIO GAIN WITH DOUBLE VOLUME CONTROL

The r.-f. input voltage to the receiver is assumed to vary up to 60 db. above some minimum point which has been designated zero level for input.

The audio output voltage from the receiver is to be varied by the listener from some minimum value called zero level for output up to a point 60 db. above zero.

The gain of the receiver is assumed just sufficient to give maximum audio output (60 db.) with the minimum r.-f. input (0 db.), the gain controls being adjusted to minimum attenuation.

Control must therefore take place over a range of 120 db. and 60 db. is assumed placed in the r.-f. control and 60 db. in the audio control, these controls being ganged together so that the attenuation introduced by one is always equal to the attenuation introduced by the other.

The modulation is assumed to be constant at some value corresponding to the average encountered in practice, and detection is assumed to be linear over the whole range.

These assumptions are not intended to agree with the conditions actually encountered in every broadcast receiver, but are useful in giving results which are indicative of the improvement to be obtained in a particular receiver by the use of a double volume control.

Figure 3.8 shows the variation in detector input voltage with variation in r.-f. input voltage and audio output level. Considering first the solid lines, which describe the conditions when using a single volume control placed in the r.-f. amplifier, it is seen that irrespective of r.-f. input voltage the detector input varies over a range of 60 db. as the audio output is varied over a corresponding range. The dotted lines show what happens when the double volume control is used. At any fixed value of r.-f. input voltage, the detector input voltage varies only over a range of 30 db. and a variation of 60 db. in detector input voltage is reached only if we go from the point of lowest input to and lowest output from the receiver, to the point of highest input to and highest output from the receiver. R.-f. inputs of moderate or high value are the cases of most importance as regards quality of detection, both because of the fact that for the greater part of the time the receiver will be tuned to powerful signals and also because with weaker signals atmospheric noise or interference renders poorer quality less noticeable. For these cases the input voltage to the detector remains within comparatively narrow limits, and is always near its maximum value. The importance of this latter condition in linear detection need not be emphasized here. Points lying in the shaded areas represent excursions of detector input voltage which take place in a receiver using a single volume control, but which do not occur when two volume controls are used.

Figure 3.9 shows the reduction in gain of the audio amplifier which takes place at various input r.-f. voltages to the receiver, and various audio output voltages. These curves then represent two things:-

1. The increase in gain which may be permitted the r.-f. amplifier, and

2. The decrease in level of noise generated in the detector or in subsequent circuits ahead of the audio gain control.

Distortion in the r.-f. amplifier only becomes apparent at high signal voltages, and fig. 3.9 shows that it is at the higher signal voltages that the greatest improvement is gained by the use of a double volume control. The improvement in audio noise is of importance only at the lower output levels and at these levels the reduction in noise level is seen to be from 30 db. to 60 db. Furthermore, it is principally at the higher signal voltages corresponding to local stations free from interference and static that noise reduction is chiefly valuable; thus the improvement in noise due to the double gain control will approach 60 db. in the most important cases.

It is believed that a case has been established for the dual volume control. The practical application of the principle should not be difficult. Additional cost of the volume control can be justified by the improvement in performance of the receiver, and by savings made possible by less careful filtering of the detector plate voltage supply. Furthermore, in receivers arranged to operate as electric phonographs the second volume control can perform the functions of the phonograph volume control, thus giving radio and phonograph volume control from a single knob, in itself a result of considerable value, and a double radio volume control at no extra cost.

3.(10) A.V.C. in Superheterodyne Receivers.

Under this heading are several aspects of A.V.C. circuits as applied to broadcast receivers put on the Canadian and American market late in 1932, and during 1933. The foregoing discussion was written and applied particularly to receivers designed before this time.

At the present time, due principally to loosening of patent restrictions, the superheterodyne or double-detection type of circuit is extensively used in radio broadcast receivers in even the lowest price classes. This circuit varies the A.V.C. problems in several ways. In the first place, the designer can readily obtain sensitivity and selectivity superior to that secured by the best tuned radio-frequency circuit. At the same time the improved performance in these respects focuses attention on the weaker parts of the design, for example the detector. Hence the advent of the superheterodyne has both made possible, and created a demand for diode detectors, with the concomitant diode A.V.C. circuits. The duo-diode tube particularly has found wide application. One of the principal advantages of the diode A.V.C. circuit is that bias voltage is developed by rectification of the modulated high-frequency voltage at the detector grid, and thus an additional plate potential of 45 volts or so is not demanded from the power source, as is the case with the circuit using a triode or tetrode. The circuit details work out so that it is usually difficult for the designer to arrange his battery supply circuits to secure a constant value of potential for the plate of the A.V.C. tube. Variations are due to the fact that a potentiometer circuit is universally employed to secure this voltage from the main plate and grid supply, and a variable current flows in this circuit due to the changing plate current in the amplifier tubes caused by the A.V.C. action. This feature makes the diode circuit very attractive.

In the superheterodyne there is commonly no or at most a single r.-f. stage, and either one or two intermediate-frequency stages. There are thus frequently less than three amplifier tubes, and so the A.V.C. action is commonly applied to the first detector also. The circuit is quite straightforward, but in addition to the data previously used for calculating the A.V.C. action it is necessary to use a curve of the "conversion conductance" versus grid bias, for the particular tube and with the proper value of local oscillator voltage. The conversion conductance may be defined as the slope of the curve relating intermediate-frequency output current into zero load, and the signal voltage on the grid.

A further feature of interest which to date has not been treated in the technical press, is the question of modulation distortion in the intermediate-frequency amplifier tubes. The work has only been done for tubes working into impedances small in comparison with the plate impedances. In superheterodyne receivers the intermediate-frequency tubes commonly work into an impedance about equal to their plate impedance. Just what effect this will have is open to question, but it will undoubtedly modify the distortion considerably.

Several refinements of A.V.C. circuits have been incorporated in the newer receivers, such as intercarrier noise suppression. In this circuit the grid bias on one of the audio amplifier tubes is normally high, so that the tube effectively blocks incoming noise. When a carrier is found sufficiently strong to operate the A.V.C. circuit, the high bias is removed from the audio tube and the circuit operates normally.

4. VACUUM-TUBE WATTMETER

4.1 Statement of the Problem

There exists a considerable field for a wattmeter suitable for use at frequencies much higher than power frequencies, and also suitable generally for measuring small amounts of power. This means that the wattmeter must have a high sensitivity. In addition, the meter should be suitable for use on a frequency range of several octaves and have a high-frequency limit of not less than 10,000 cycles and preferably several thousand kilocycles.

A wattmeter which successfully meets these requirements was invented by Eugene Peterson and has been described by McNamara and Turner (Ref. 40). This meter uses two identical 3-electrode vacuum tubes, in a push-pull or series circuit relation. A micro-ammeter reads the difference between the d.-c. plate currents of the two tubes. Two voltages are secured from the circuit in which the power is to be measured, these voltages being in phase with and proportional to the load voltage and load current, respectively. By a simple circuit arrangement the instantaneous sum of the two voltages is applied to one tube and the difference to the other tube. The paper cited shows that the d.-c. meter reading is then closely proportional to the power in the circuit, even if non-sinusoidal wave forms are encountered, and if the tube characteristics depart from simple ideal functions. This wattmeter is eminently satisfactory, but it was hoped that some arrangement could be developed which would not involve close matching of tubes, and the unavoidable drift in calibration due to slight changes in tube characteristics.

4.2 Proposed Method

There appear to be possibilities in the use of a vacuum tube as the essential part of a wattmeter. The arrangement to be described has shown results which were at least encouraging, and perhaps amenable to further development.

Briefly, the essential idea is to use a tube with three or more electrodes, the anode current being a function of two independent voltages, for example, of the grid and anode potentials with respect to the cathode in a three-electrode tube. The operating conditions are then adjusted so that the anode current is a non-linear function of the electrode voltages. Under these conditions, we know that if alternating potentials of the same frequency are applied to the electrodes, there will flow in the plate circuit a current made up of a direct-current component, and a number of other components whose frequencies are integral multiples of the exciting voltage. In general, the amplitude of these components depend in a rather complicated way upon both the amplitude and phase relations of the two exciting potentials. Hence there is the possibility of so adjusting operating conditions that one component of plate current, preferably the d.-c. component, will be proportional to the product of the amplitudes of the exciting potentials, and to the cosine of their angle of phase difference. If this condition can be secured the extension of the circuit for use as a wattmeter is obvious.

4.3 Mathematical Analysis

Let us first consider the general case where the plate current is a continuous function of the electrode potentials, and hence for our purpose may be represented as a finite power series in the potentials.

Let the instantaneous electrode potentials be p and g, and the instantaneous plate current i

Then
$$
\begin{aligned}
i = \; & a_0 + a_1 g + a_2 g^2 + a_3 g^3 + \ldots\ldots\ldots\ldots \\
& + b_1 p + b_2 p^2 + b_3 p^3 + \ldots\ldots\ldots\ldots \\
& + c_1 gp + c_2 g^2 p + c_3 gp^2 + \ldots\ldots\ldots\ldots
\end{aligned} \qquad (1)
$$

where the a's, b's, and c's are constants depending on the particular tube and circuit conditions.

Now if $g = G \cos wt$ (2)

and $p = P \cos(wt + \theta)$ (3)

we may calculate from (1) the change in the d.-c. component of i due to p and g. At once it is seen that it is desirable to have the coefficients, a_0, a_2, a_3, b_2, b_3, etc. all extremely small or zero, as they each contribute d.-c. terms to i which do not meet the desired conditions, their amplitude being dependent on a single potential only. The terms with c-coefficients give rise to d.-c. components as shown below.

Term	D.-C. Components
c_1gp	$1/2\ c_1GP \cos\theta$
c_2g^2p	0
c_3gp^2	0
$c_4g^2p^2$	$1/8\ c_4G^2P^2 \cos 2\theta$
$c_5g^3p^2$	0
$c_6g^2p^3$	0
$c_7g^3p^3$	$1/32\ c_7G^3P^3 \cos\theta - 1/32\ c_7G^3P^3 \cos 3\theta$

The important term is seen to meet both our conditions, and the other terms which do not satisfy our requirements will usually be small, since they include fractional factors, and high-ordered coefficients, which are small in value.(1)

(1) It is not at once obvious why a high-order coefficient such as c_7 should be small in a power series of the type considered. We cannot say, Nature prefers to work simply, and hence allows us to approximate the tube characteristic with a few terms and allows us to neglect all higher terms, assuring us that none will be large in value. This not more reasonable than saying Nature abhors a vacuum. Also it is not always true in parallel cases. For example, in the note of some reed instruments, notably the oboe, certain of the higher harmonics are much greater in amplitude than the lower harmonics. The reason why the high-order coefficients are small is rather to be found in the mathematics of artificially breaking down a continuous function into a power series.

It is now seen that the ideal tube characteristic can be expressed as follows:-

$$i = a_0 + a_1 g + b_1 p + c_1 gp + c_2 g^2 p + c_3 gp^2$$

where one or more of the coefficients may be zero, with the exception of $\underline{c_1}$

It is interesting to consider the characteristic surface represented by the above equation. If the $\underline{c}$'s are all zero, the surface is a plane cutting the co-ordinate planes at angles other than 90 . If other small terms are present the surface is sharply curved near the plane $i = a_0$. This is the usual surface found to hold for a three-electrode tube over its useful range of operating conditions. If now we admit the term $\underline{c_1 gp}$ and especially if this term is to be large, the characteristic surface is essentially different. If a family of planes parallel to one co-ordinate plane, and equally spaced along the other co-ordinate plane, be passed through the characteristic surface, the intersections will all be along straight lines, which have slopes which vary uniformly from one line to the next.

A case that is interesting in view of the experimental results is obtained by using only first and second order terms of equation (1)

$$i = a_0 + a_1 g + a_2 g^2 + b_1 p + b_2 p^2 + c_1 gp$$

The direct current terms are found to be:

$$i_{d.-c.} = a_0 + 1/2\, a_2 G^2 + 1/2\, b_2 P^2 + 1/2\, c_1 GP \cos\theta$$

Then if P is plotted against G the locus of $i_{d.-c.}$ is in general an ellipse.

4.4 Experimental Results

In the experimental work the main problem was to find a vacuum tube with a suitable characteristic plane. Three-electrode tubes were first tried, and were readily shown to be of little value. However, complete static curves were made of a Northern Electric 244-A vacuum tube, in an effort to find some circuit condition which would give the desired characteristics. This tube is a general-purpose heater-type tube.

In fig. 4.1 the static curves are shown. It is seen that the characteristic surface is nearly a plane without the continually changing slope postulated as necessary.

At this stage it was thought that the three-electrode vacuum tube with negative grid and without grid or plate emission held no promise of satisfactory results. Accordingly measurements were made on a four-electrode tube, the Northern Electric 259A vacuum tube. This is a small screen-grid heater-type tube. It was hoped that the division of cathode emission between screen and plate might provide the characteristic being sought. The control-grid and screen-grid voltages would have added to them the exciting potentials.

In fig. 4.2 are shown a group of mutual grid-plate curves on this tube, both with and without a resistor in the plate circuit (200,000 ohms). There is seen to be some small change of slope, and it is indeed a well-known fact that the transconductance of a screen-grid tube is influenced by the screen voltage. Actual battery voltages are shown in each curve. While static curves of this kind do not convey a great deal of information, yet they show the existence of general characteristics. These curves showed sufficient promise so that it was thought worthwhile to make some actual

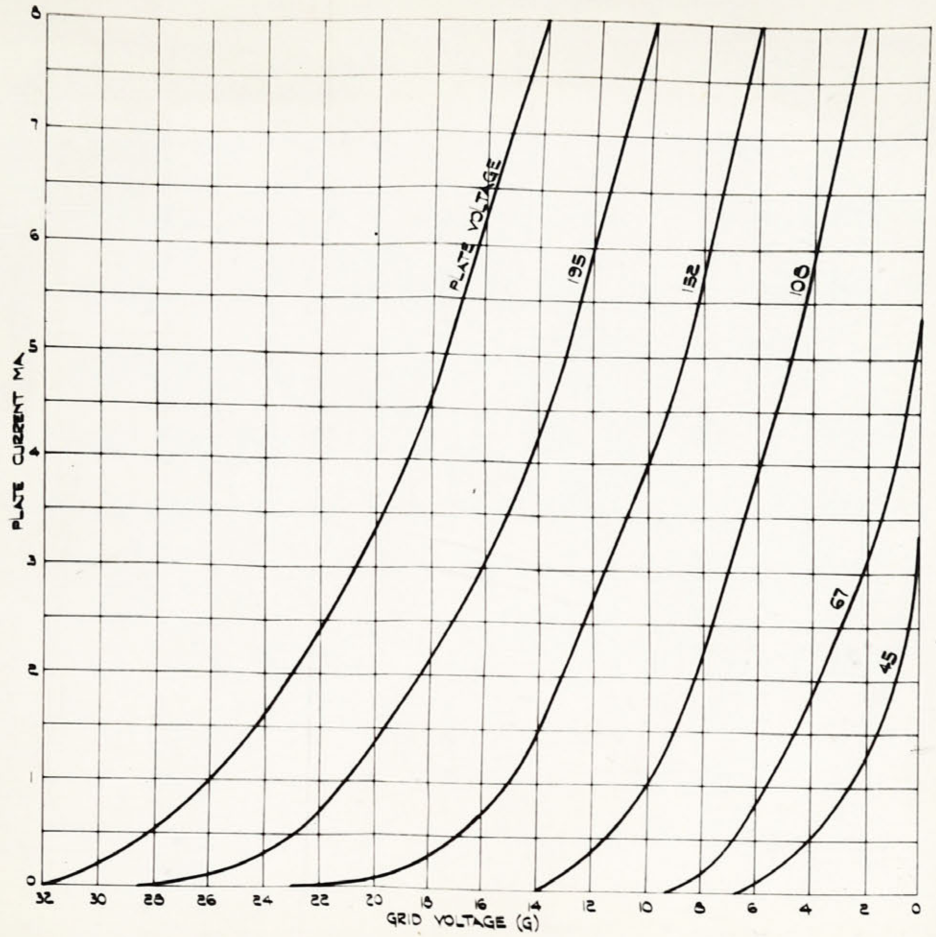


FIG. 4.1
STATIC CHARACTERISTICS OF N.E. 244-A VACUUM TUBE #24001
NO RESISTANCE IN PLATE CIRCUIT

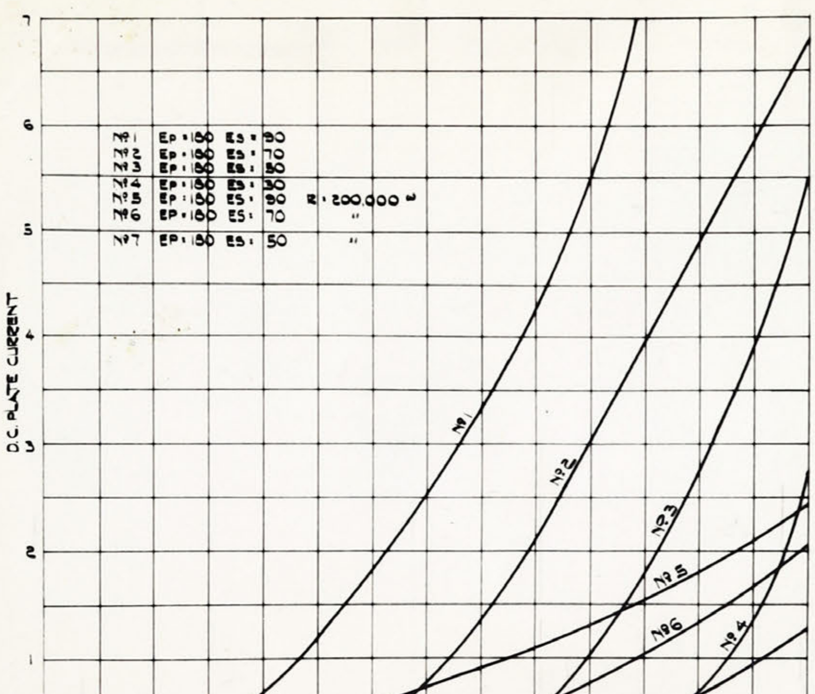


FIG. 4.2
STATIC CHARACTERISTICS OF N.E. 259-A VACUUM TUBE #29966

measurements using the tube as a wattmeter.

Accordingly a measuring circuit was set up. This circuit was arranged so that an a.-c. voltage of known magnitude and phase difference could be applied to the control grid and the screen grid. The procedure followed was to hold the a.-c. grid voltage constant at 3 volts r.m.s., and vary the relative phase and amplitude of the screen voltage through a considerable range. The curves of fig. 4.3 show the resulting plate currents.

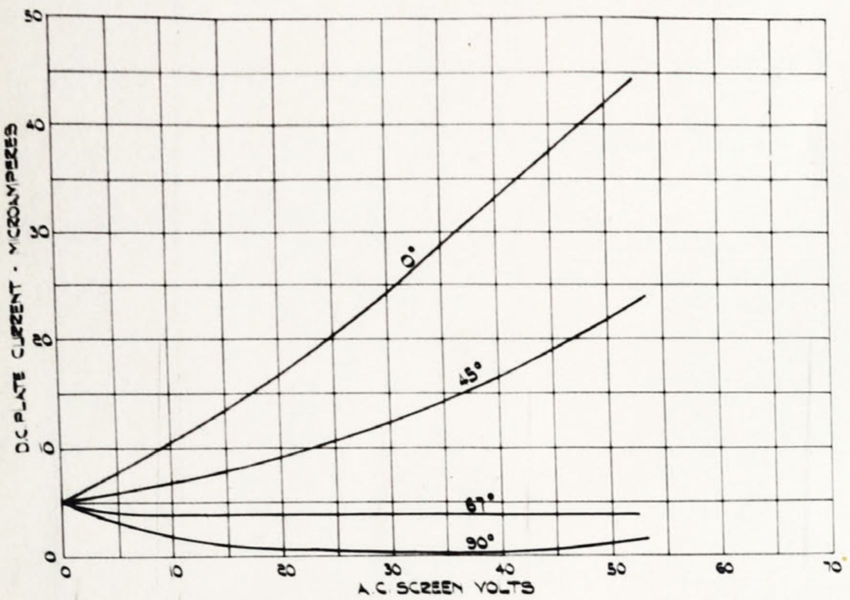


FIG. 4.3
WATTMETER CURVES N.E. 259-A VACUUM TUBE #29966

It is seen that a considerable degree of success has been obtained. That is, the plate current is proportional to the true power for phase angles of from 0° to more than 45°. Above this value the results are less useful. At 67° the plate current is nearly constant for all values of screen voltage, and above 67° the plate current falls off slightly as the screen-grid voltage is reduced. Thus the arrangement is not suitable as shown for a wattmeter, but at the same time the behaviour at small phase angles justifies the belief that the circuit is capable of great improvement. It is probable that no tube commercially available at present will satisfy the requirements of this circuit and that a tube designed for this purpose is necessary. Such a design might well take the form of a co-planar-grid tube, with one grid positive, the other negative. Such a tube can probably be designed with a sufficient degree of interaction between the two grids to give the desired characteristic.

5. NOTES ON THE HETERODYNE DETECTOR

5.1 Introduction

The following notes on the use of a screen-grid valve as a first, or heterodyne, detector in a super-heterodyne receiver are intended as an amplification of an article by E.C.L. White, entitled "The Screen-Grid Valve as a Frequency-Changer in the Super-Het," which appeared in the "Wireless Engineer", November 1932.

5.2 The Problem

White discusses the so-called "new" circuit for the heterodyne detector, in which the local oscillations are introduced into the anode circuit. This is, of course, similar to the usual anode modulation circuit, but the conditions for modulation are different to those with which we are more familiar. White points out first that modulation can take place even when the anode-voltage anode-current, and grid-voltage anode-current relations are both linear. Further, from measurements on a particular valve he shows that maximum efficiency is not obtained when the valve is biased to the knee of the grid-voltage anode-current curve. The analysis of the general case establishes these results, except that modulation is shown to be due to the variation of the plate resistance with grid-voltage, and not to variation of μ as stated by White, and shows other desirable operating conditions.

5.3 Mathematical Analysis

Let the variable part of the anode-current, i_a, over the operating range depend in the most general way on the variable part of the anode voltage, p, and the variable part of the control-grid voltage, g.

$$
\begin{aligned}
i_a &= a_1 p + a_2 g + \cdots \qquad \text{----------- (1)} \\
&+ a_3 p^2 + a_4 g^2 + a_5 gp + \cdot \\
&+ a_6 p^3 + a_7 g^3 + a_8 p^2 g + a_9 pg^2 \\
&+ a_{10} p^4 + a_{11} g^4 + a_{12} p^3 g + a_{13} p^2 g^2 + a_{14} pg^3 \\
&+ \; . \; . \; . \; . \\
&+ \; . \; .
\end{aligned}
$$

The <u>a's</u> are constants for the particular valve under discussion, and depend in general on the fixed values of grid voltage and anode voltage about which <u>g</u> and <u>p</u> are variations.

For the sake of ease of manipulation and also because, as we shall see, higher order terms are not important in practical cases, we shall consider only the terms of power four or less. Let the voltage introduced in the grid circuit be a sine wave of radian velocity w_1 and amplitude A, modulated by a second sine wave of radian velocity w_2, the depth of modulation being M.

Then $g = A \cos w_1 t \, (1 + M \cos w_2 t)$ -------- (2)

Let the local oscillator voltage have a radian velocity w_3, and amplitude B.

Then $p = B \cos w_3 t$ -------- (3)

No general phase relations have been assumed between the three sine waves, as it can be shown that this is not necessary to obtain general results. By inserting relations (2) and (3) in equation (1) and expanding in first power cosine terms, the current which is passed on to the intermediate-frequency amplifier from the detector may be determined. The only terms of interest are those made up of expressions of the form $\cos(w_1 - w_3 \pm nw_2)t$ where n is zero or an integer. These expressions represent the carrier and sidebands at the intermediate frequency. Performing the indicated operations we find:-

$$
\begin{aligned}
i_a = {} & AB\cos(w_1 - w_3)t \left[1/2\, a_5 + 3/8\, a_{12}B^2 + 3/8\, a_{14}A^2 \left(1 + \frac{3M^2}{2}\right)\right] \\
& + \frac{M}{2} AB \left[\cos(w_1 - w_3 + w_2)t + \cos(w_1 - w_3 - w_2)t\right] \left[1/2\, a_5 + 3/8\, a_{12}B^2 + 9/8\, a_{14}A^2 \left(1 + \frac{M^2}{4}\right)\right] \\
& + \frac{9}{32} a_{14} M^2A^3B \left[\cos(w_1 - w_3 + 2w_2)t + \cos(w_1 - w_3 - 2w_2)t\right] \\
& + \frac{3}{64} a_{14} M^3A^3B \left[\cos(w_1 - w_3 + 3w_2)t + \cos(w_1 - w_3 - 3w_2)t\right]
\end{aligned}
\qquad (4)
$$

The first term represents the carrier at the intermediate frequency, the second term the upper and lower sidebands due to the modulation frequency, and the third and fourth represent respectively the sidebands which contain second and third harmonics of the modulation frequency.

An examination of equation (4) yields the following information:-

1. There is an increase in depth of modulation through the first detector when $\underline{a_{14}}$ is positive. This will result in distortion upon demodulation by the second detector when the apparent modulation is greater than unity. That is, approximately, when

$$M \left[1/2\, a_5 + 3/8\, a_{12} B^2 + 9/8\, a_{14} A^2 \left(1 + \frac{M^2}{4}\right) \right]$$

is greater than

$$1/2\, a_5 + 3/8\, a_{12} B^2 + 3/8\, a_{14} A^2 \left(1 + \frac{3M^2}{2}\right)$$

Such will be the case only when $\underline{M}$ is near unity, as both $\underline{a}$ and $\underline{A}^2$ are ordinarily small. Thus this does not constitute an important source of distortion.

2. There are present in the output sidebands involving the second and third harmonics of the modulation frequency. There will ordinarily be sufficient carrier present to demodulate these terms, but they will in any case be small as they have a factor $\underline{A}^3$,

which will ordinarily be very small in comparison with AB.

3. It is to be noted that the odd-powered terms of equation (1) contribute nothing to the modulation products delivered to the intermediate-frequency amplifier. The terms of power two contribute no distortion, this is caused by terms of power four or greater. Thus if the valve characteristics are such that the family of anode-voltage anode-current curves and also the grid-voltage anode-current are all parabolas or cubics, the first detector will be distortionless. Note also as a matter of interest that if all the *a*'s except a_1, a_2 and a_5 are zero, distortionless modulation will result, even though the anode-current anode-voltage and anode-current grid-voltage relations are then everywhere linear. The characteristic surface becomes a twisted plane. If the characteristic surface is a true plane then $a_5 = 0$, and no modulation takes place.

4. Assuming that the shape of the characteristic does not change appreciably due to changing inputs, least distortion will result with as small a signal voltage, and as great a local oscillator voltage as possible.

5. For maximum gain the local voltage should be high, and the grid should be biased to the point at which a_5 is a maximum, assuming that a_{14} is small. For a

discussion of the evaluation of $\underline{a_5}$ see Peterson and Evans, "Modulation in Vacuum Tubes Used as Amplifiers", Bell System Technical Journal, July, 1927. $\underline{a_5}$ corresponds to their parameter $\underline{b_{11}}$, which is shown to be equal to

$$\frac{\partial_2 I_a}{\partial E_p \partial E_g} \quad \text{or} \quad \frac{-1}{R_o^2}\frac{\partial R_o}{\partial E_g} ,$$

where E_p and E_g are the anode and grid voltages I_a is the anode current, and R_o is the anode impedance all evaluated at the operating point. Thus the best condition for modulation does not require the amplification factor of the valve to vary, so that the application of the circuit is not limited to screen-grid valves. The above analysis, however, applies exactly only where the load impedance is small compared to the anode impedances of the valve, and this will ordinarily be the case only with screen-grid or pentode valves.

5.3 Conclusion

These results indicate that the first detector can be expected to be free from distortion, and provide a means for finding the best operating conditions. The analysis, it should be noted, also applies directly to the rather important case in which the local oscillations are introduced into the circuit of a second grid of the heterodyne-detector valve, instead of the anode. A complete analysis would include a consideration of the effects of the load impedance on the operation of the heterodyne detector, but such an analysis is outside the scope of the present discussion, which can be extended directly only to the case in which the load impedance is a constant pure resistance. The procedure is given by Peterson and Evans in the paper already mentioned. By a comparison of equation (1) of the present discussion with equation (3) of their paper, the corresponding tube parameters can be written down. Then by a substitution into equations (6) and (4) of their paper, the expression for the anode current can be obtained, and broken down to give the modulation products in the usual manner. The procedure for a generalized load impedance is given by F.B. Llewellyn, "Operation of Thermionic Vacuum Tube Circuits", Bell System Technical Journal, July, 1926.

6. CONSTANT-IMPEDANCE COUPLING CIRCUITS

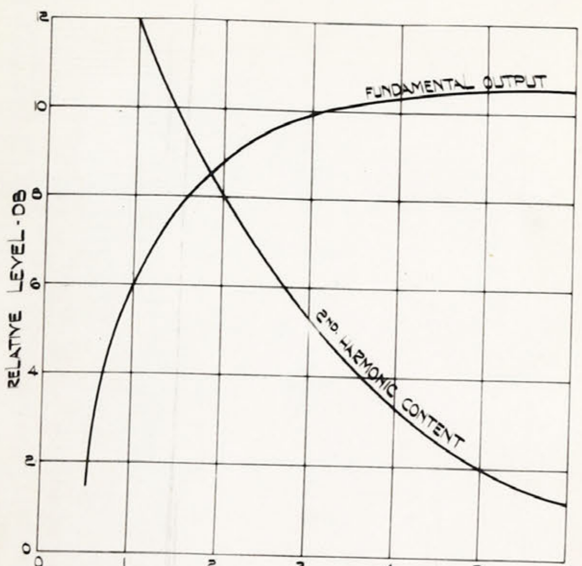
6.1 Statement of the Problem

The material of this section, while applicable generally wherever a vacuum-tube amplifier is to be coupled to a load circuit whose impedance is a function of frequency, finds particular application where a pentode tube is to be coupled to a loud-speaker. Here, also, the non-linear feature of the circuits involved is of particular importance. Before the coupling is considered, it might be of advantage to discuss the conditions in a pentode tube which necessitate special circuit design.

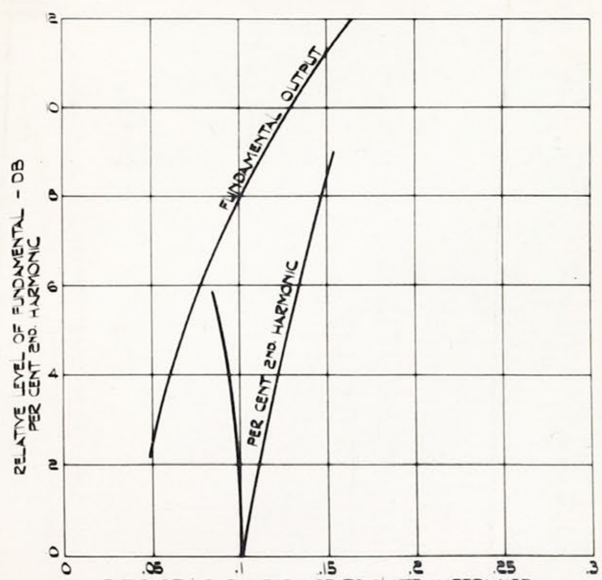
A three-electrode tube supplying power to a loud-speaker is ordinarily connected so that it faces from one to five times its own plate impedance. Under these conditions harmonic generation due to non-linearity of the mutual characteristic is effectively reduced, and approaches a minimum value as the load impedance is raised. This minimum value is not zero, due to what has been called "μ-modulation", i.e. harmonic generation caused by a variation in the amplification factor (μ) of the tube, as the grid and plate potentials are varied. The harmonic content due to "r_p- modulation", or a variation in the dynamic plate resistances (r_p) with variation in operating potentials, is ultimately reduced to zero with an increasing load resistance. The whole question of harmonic generation in amplifiers has been thoroughly treated by

Peterson and Evans in the paper cited above.

The foregoing discussion refers only to resistive loads. Where the load has an appreciable reactive component, almost invariably inductive in the case of loud-speakers, further complications follow. The harmonics of the fundamental frequency being transmitted by the tube are relatively magnified due to the fact that the dynamic mutual characteristic becomes a loop, somewhat similar to a hysteresis loop for a magnetization cycle of iron. Also, since the load impedance is relatively higher for the harmonics than for the fundamental, a greater proportion of the generated harmonics builds up across the load impedance, and moreover high-frequency fundamentals are transmitted with greater efficiency than are low-frequency fundamentals. This feature is of course also of importance where resistive loads are encountered. Fig. 6.1 shows graphically the total harmonic generation, and



RATIO OF LOAD IMPEDANCE TO PLATE IMPEDANCE
EFFECT OF LOAD VARIATIONS WITH TYPICAL TRIODE
(N.E. 262-A VACUUM TUBE)
PLATE VOLTAGE 157.5, GRID BIAS 8.0 VOLTS
A.C. INPUT TO GRID 8.0 VOLTS PEAK
FIG. 6.1



RATIO OF LOAD IMPEDANCE TO PLATE IMPEDANCE
EFFECT OF LOAD VARIATIONS WITH TYPICAL PENTODE
(R.C.A. 38 VACUUM TUBE)
PLATE VOLTAGE 135, SCREEN VOLTAGE 135, GRID BIAS 13.5 VOLTS
A.C. INPUT TO GRID 13.5 VOLTS PEAK
FIG. 6.2

relative voltage developed across the load impedance, for a typical triode with various ratios of plate load to internal plate impedance. Since triodes are commonly connected so that this ratio is a minimum of unity, variation in load impedance is seen not to be of great importance. It should be borne in mind, however, that a reactive load impedance may cause considerable impairment of quality, apart from the changing modulus, for the reasons given above.

In the pentode tube, conditions are very different. High-velocity electrons, due to high screen voltages, cause considerable irregularity in the mutual characteristics, and the division of cathode emission between plate, screen, and suppressor grid, causes an effective μ-modulation of considerable proportions. This is 180° out of phase with the r_p-modulation, and hence it is possible by selecting the correct plate load, to make the absolute values of the second harmonic voltages due to each cause equal; they then nullify one another, and only third and higher harmonics remain. Thus it is of considerable importance for this reason to use load impedances which are resistive and reasonably constant in value over the frequency range to be transmitted.

A further factor which is of importance, is that the optimum loads for usual types of pentodes are from one-tenth to one-fifth the internal plate impedance of the tube. Fig. 6.2 shows the relative harmonic distortion, and the relative fundamental amplitude as the plate load is varied with a typical pentode tube. It is seen that on both counts an extremely constant load impedance is desirable.

In intermediate amplifiers it is usually possible to arrange the circuit so that the tubes work into relatively pure and constant resistances. Where, however, the tube must work into a load with a reactive component, such as a loud-speaker or oscillograph coil, special coupling circuits must be employed. Since usually it is desired to transmit considerable power to the load circuit, it is not permissible to use a resistive attenuation network to equalize impedance variations.[(1)]

In the important case of a loud-speaker, impedance variations are due to several factors. The voice coil possesses in some cases considerable inductance, and above the frequency of mechanical resonance the diaphragm usually couples an inductive impedance into the circuit. At low frequencies the primary inductive reactance of the output transformer may constitute the governing impedance. There is further a considerable variation in effective resistance of the voice coil, and in the coupled mechanical resistance due to variation in acoustic radiation.

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(1) There appears to exist a theorem which relates the attenuation introduced into a circuit, by an equalizing network made up of resistive components, to the effective equalization achieved by the network. This theorem seems not to have been stated, but would be of considerable importance, in the circuit of the 22-type telephone repeater, for example.

Characteristics of a typical loud-speaker are shown in fig. 6.3

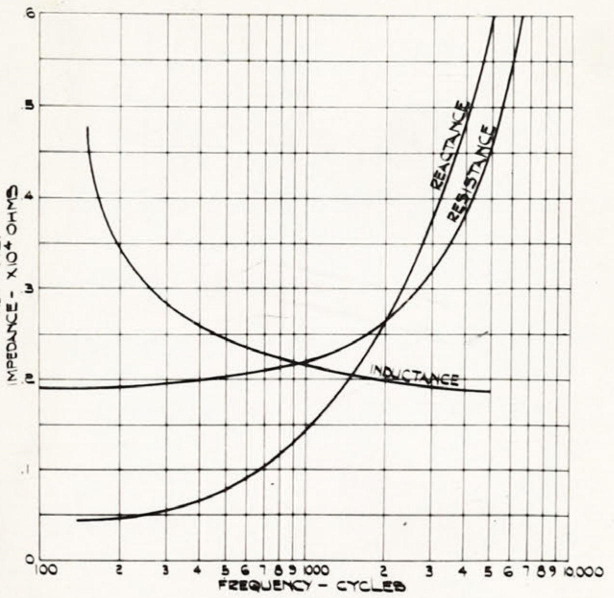

FIG. 6.3
TYPE A-150 MAGNAVOX SPEAKER
WITH 32 : 1 OUTPUT TRANSFORMER

While many speakers will show a more irregular variation in impedance than these measurements indicate, such irregularities usually occur near the low-frequency end, where their importance is lessened. The measurements shown were taken on an ordinary shielded a.-c. bridge, with the loud-speaker free to radiate, and the rated field current flowing.

6.2 Method Proposed for Solution

The obvious method for solution is to connect some sort of an equalizer between the vacuum tube and the variable load. Resistance networks are ruled out, and also complicated networks in general, as these generally involve considerable attenuation and are expensive. The plan commonly used has been to connect a resistance and capacity in series across the loud-speaker, as this tends to hold down the high-frequency impedance. The present discussion will lead to a refinement of this scheme that has not been previously applied, as far as is known.

6.3 Mathematical Analysis

Consider the circuit of fig. 6.4. Here L and R_2 represent the inductance and resistance respectively of the loud-speaker, and R_1 and C are the elements of the equalizer. It is desired to make the impedance Z a constant pure resistance. The value of Z may be written down for any frequency,

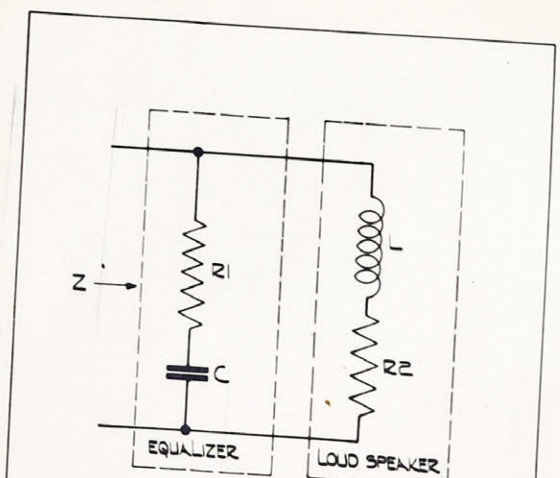

FIG. 6.4
SCHEMATIC CIRCUIT OF EQUALIZER

$$Z = \frac{\left(R1 - \frac{j}{\omega C}\right)\left(R2 + j\omega L\right)}{R1 - \frac{j}{\omega C} + R2 + j\omega L}$$

$$= \frac{R1R2 + \frac{L}{C} + j\left(\omega L R_1 - \frac{R_2}{\omega C}\right)}{R_1 + R_2 + j\left(\omega L - \frac{1}{\omega C}\right)}$$

Rationalizing, and setting the imaginary part equal to zero, we get:

$$R_1 = R_2$$
$$= \sqrt{\frac{L}{C}}$$

and

$$Z = R_1$$

This then, gives the value of R_1 and C which must be used to give a constant impedance. It is interesting to note, that since no resonance phenomena are involved, the circuit has an ideal response to transients also.

In many cases, of course, it is not correct to represent R_2 and L as constant. An attempt was made, by assuming simple laws of variation, to find a network which would give results for this case equal to the simpler case. No success was achieved, and it is believed that equalization of even a case where R is proportional to ω, and L is proportional to $\frac{1}{\omega}$, is possible only with an elaborate network, if at all.

7. USE OF DEGENERATION IN AMPLIFIERS.

7.1 Statement of the Problem.

In addition to the considerations of section 6.1, other factors should be discussed which bear on the problem of coupling a tube to a variable load. In most cases, the gain of the stage so coupled is not of great importance. As a general rule gain can be obtained very cheaply in preceding stages, and if a circuit layout has advantages in other respects, low gain is of small moment. This statement applies even to the pentode tube, which originally gained a field due to its comparatively high amplification, but is now used principally in applications where its relatively high plate efficiency is particularly desired.

In many applications it is satisfactory to allow the load impedance to fluctuate, as long as the voltage across the load does not vary. That is, we wish to arrange the vacuum tube so that it becomes a constant voltage, or low impedance device. The ordinary pentode, due to its relatively high plate impedance, is practically a constant current device, and the triode lies between these two limits, tending towards the constant voltage. Briefly, in section 6 there was developed a method of equalizing the load, in this section we wish to operate on the vacuum tube to render it unaffected by load conditions. It should be pointed out that the present circuit does not minimize harmonic generation in the pentode, but simply holds the load voltage constant over a wide frequency range.

7.2 Proposed Solution

The method of obtaining the desired characteristics is simply to couple back the plate circuit of the vacuum tube to its grid through a low-impedance element, so as to secure a degenerative effect. The input voltage is then introduced in series with the feed-back circuit, and the output load is coupled to the plate circuit in the usual way. We have now an amplifier connected to give an amount of degeneration which is substantially independent of frequency. At the same time the feed-back circuit consumes no power from the plate circuit, and input impedance is still practically infinite.

The physical behaviour of the circuit is as follows: The voltage built up across the output load increases ordinarily as the load impedance rises. In the present case, however, due to the degeneration the gain is normally greatly reduced, but as the output voltage tends to increase, the feed-back coupling is in effect increased, and the resulting lowered gain results in the voltage remaining approximately constant.

7.3 Analysis of Circuit.

The skeleton schematic is shown in fig. 7.1, where the input voltage

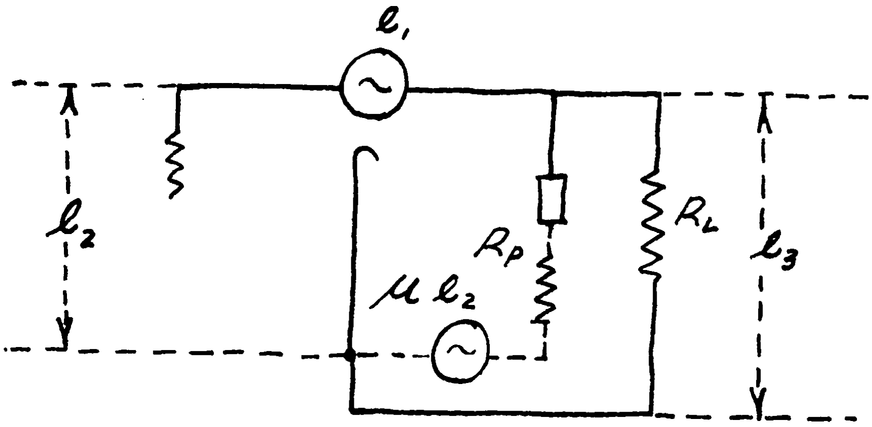

FIG. 7.1

is e_1, the output voltage e_3, and the other symbols have the usual meanings. We may also define two quantities, μ' and R_p', which bear the same relation to e_1 and e_3 that μ and R_p do to e_2 and e_3. Then we may write,

$$e_3 = \frac{R_L}{R_L + R_p} \cdot \mu' e_1 \qquad \text{----- (1)}$$

also
$$e_3 = \frac{R_L}{R_L + R_p} \mu e_2 \qquad \text{----- (2)}$$

and
$$e_2 = -e_3 + e_1 \qquad \text{----- (3)}$$

Substituting (3) in (2), we have

$$e_3 = \frac{R_L}{R_L + R_p} \cdot \mu (e_1 - e_3) \qquad (4)$$

Then from (4) and (1), we obtain,

$$\mu' = \frac{\mu}{\mu + 1} \qquad R_p' = \frac{R_p}{\mu + 1}$$

Then as far as the voltage across the load in the plate circuit is concerned, the tube acts as though it had a plate resistance $R_p' = \frac{R_p}{\mu + 1}$, and thus since in the case of many tubes, (notably pentodes), this is only a fraction of the usual plate resistance, and also of the plate load impedance, the voltage appearing across the plate load impedance is substantially independent of the latter. Hence, for example, in the case of a pentode coupled to a loudspeaker whose impedance varies widely with frequency equalization of the audio voltage across the speaker is secured without the use of impedance equalizing devices which cause power loss between the tube and speaker.

It is true that a considerable amount of amplification has been lost, as the figure of merit, $\frac{\mu^2}{R_p}$ is greater than $\frac{\mu'^2}{R_p'}$, by a multiplying factor $\frac{1}{\mu + 1}$. This loss is usually of small importance, as the mutual conductance remains unchanged, and the plate-circuit efficiency is the same. Also the input impedance continues to be infinite.

The principle of the circuit can further be extended to any amplifier circuit to improve the frequency characteristic, whether the defect is due to a varying load impedance or not. For if the voltage across the load is transferred back to the input in a manner similar to the circuit shown, then the amount of degeneration secured at a given frequency depends on the efficiency of the whole amplifier at that frequency, and a corresponding reduction in gain takes place. Thus equalization of response can be secured automatically in a manner similar to that demonstrated by the curves.

The advantage of the present circuit over a circuit employing degeneration by any usual method such as a reversed magnetic feed-back connection is that the input impedance is infinite, and its advantage over a circuit using impedance or any other type of equalization is its simplicity, exactness, and efficiency, there being no loss of power due to equalization.

8. BIBLIOGRAPHY

There is listed below a number of articles dealing with the material of this thesis. No attempt has been made to give an exhaustive list, but it is thought that the principal articles have been listed, and in nearly every case the general reader can readily obtain from the articles listed a fairly complete list of publications on each topic. The articles are arranged according to the section of the thesis with which they are related. By doing this it has been possible to avoid footnotes throughout the text, and still secure a unity of subject matter.

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