

Some Recent Developments in the Audion Receiver

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Classic Paper

I. THE AUDION AS DETECTOR AND AMPLIFIER¹

The fundamental operating characteristic of the audion is the relation between the wing current and the potential of the grid with respect to the filament—say the negative terminal of the filament. Such a characteristic is shown in Fig. 1, and from it we see that a positive charge placed on the grid produces an increase in the wing current, and that a negative charge placed on the grid produces a decrease in the wing current. When the audion is used as an amplifier, and an alternating electromagnetic field (EMF) is impressed between the grid and the filament, the continuous current of the wing circuit will be varied in accordance with the characteristic of Fig. 1, producing on the continuous current a superimposed ac wave in phase with and of the same frequency as the impressed EMF. Diagrammatically this action is shown in Fig. 2.

The action of the audion as a detector of radio frequency oscillations is very different from its action as a simple amplifier. Some form of connection must be used, such that the effect of a group of radio frequency oscillations in the grid circuit of the audion is translated into a single audio frequency variation of the current in the telephones. The usual method is to make use of the valve action between the hot and cold electrodes at low pressures, and the connection used to do this is shown in Fig. 3. In this method of connection there are two distinct actions; one rectifying and the other amplifying. The closed oscillation circuit: LC , filament, grid, and condenser C_2 , behaves exactly as a Fleming valve receiver, the incoming oscillations being rectified between the grid and filament and the rectified current being used to charge the condenser C_2 (the

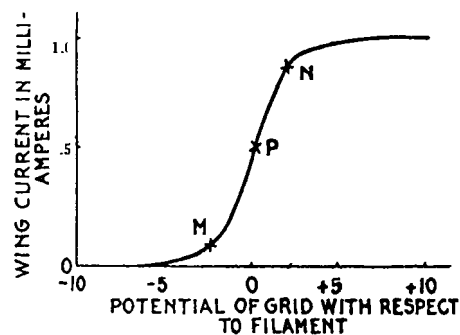


Fig. 1.

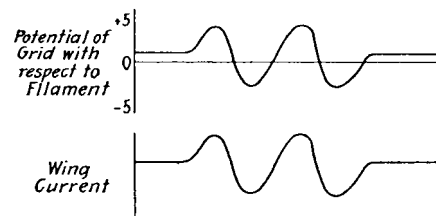


Fig. 2.

side connected to the grid being of course negative). The negatively charged grid then exerts a relay action on the wing current, decreasing it; the wing current returning to its normal value as the charge in the grid condenser leaks off by way of the grid and the grid resumes its normal potential. If the audion is properly constructed, the relay action results in an amplification of the energy available for use in the telephones over that which would be available in a simple rectifier. Fig. 4 indicates the features of the valve method of detection.

Working in conjunction with Prof. Morecroft, I have recently secured oscillograms which confirm the explanations already advanced and these oscillograms and the means by which they were obtained are herewith shown in Figs. 5–7.

It will be seen, therefore, that using the audion as a detector of radio frequency oscillations, it has been shown that in addition to operating as a rectifier it simultaneously acts

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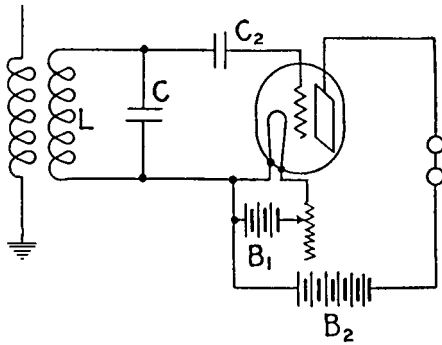


Fig. 3.

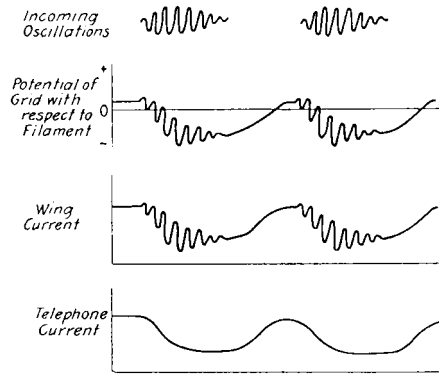


Fig. 4.

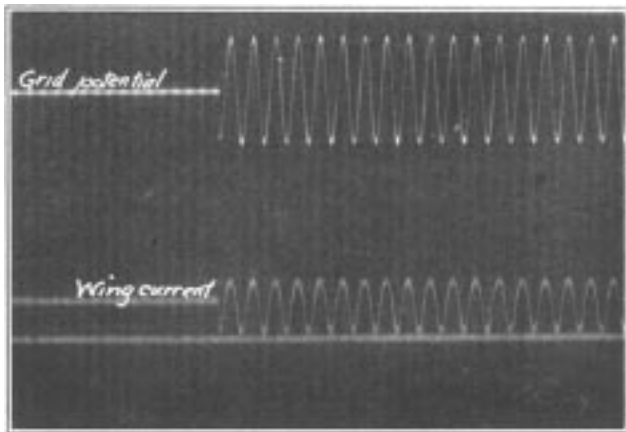


Fig. 5.

as a repeater of the radio frequencies; so that oscillations in the grid circuit set up oscillations of similar character in the wing circuit of the audion. In the ordinary detector system no use is made of the repeating action, and it is the purpose of the present paper to show that it may be turned to account to produce improvements in the reception of signals which completely overshadow any of the particular advantages of the audion when used as a simple detector. The ordinary detector circuit is illustrated by Fig. 3 and the phenomena present therein may be summed up diagrammatically by the curves of Fig. 4. It will be seen from these that the radio frequency oscillations present in the wing circuit of Fig. 3 with the ordinary audion are necessarily small and also that they are of no value in producing a response

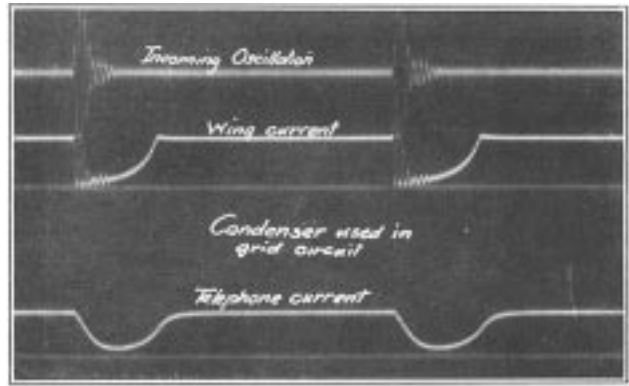


Fig. 6.

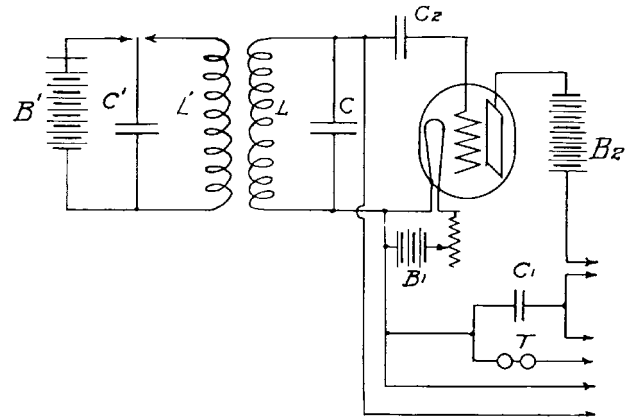


Fig. 7.

in the telephones; but by providing means for increasing their amplitude and means for utilizing them to reinforce the oscillations of the grid circuit, it becomes possible to produce some very remarkable results.

II. REINFORCEMENT OF RADIO FREQUENCY OSCILLATIONS BY THE AUDION

There are two ways of reinforcing the oscillations of the grid circuit by means of those in the wing circuit. The simplest way perhaps is to couple the two circuits together in the manner shown in Fig. 8. This is essentially the same as Fig. 3, but modified by the introduction of the inductively coupled coils L_2 and L_3 in the grid and wing circuits respectively and by the condenser C_2 which forms a path of low impedance across the telephones for the radio frequencies. In such a system, incoming signals set up oscillations in the grid circuit which repeat into the wing circuit producing variations in the continuous current, the energy of which is supplied by the battery B_2 . By means of the coupling M_2 , some of this energy of the wing oscillations is transferred back to the grid circuit, and the amplitude of the grid oscillations thereby increased. The amplified grid oscillations then react on the wing circuit by means of the grid to produce larger variations in the wing current, thus still further reinforcing the oscillations of the system. Simultaneously with this procedure the regular detecting action goes on; the condenser C_1 is charged in the

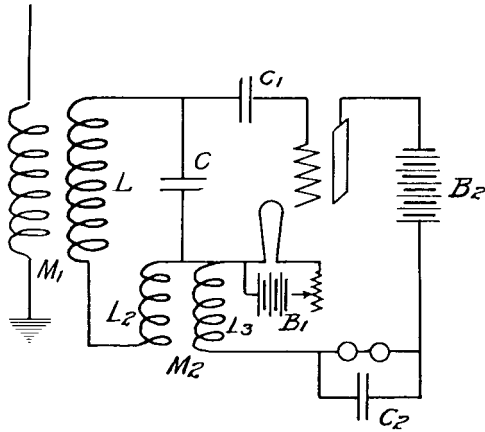


Fig. 8.

usual way, but accumulates a charge which is proportional, not to the original signal strength but to the final amplitude of the oscillations in the grid circuit. The result is an increased response in the telephone proportional to the energy amplification of the original oscillations in the grid circuit. It will be observed from the operating characteristic (the relation between grid potential and wing current), that the amplitude of the variation in the wing current is directly dependent on the variation of the grid potential. This indicates that the grid circuit should be made up of large inductance and small capacity to obtain the maximum voltage which it is possible to impress on the grid. For moderate wave lengths the tuning condenser C of the grid circuit may be omitted altogether and the capacity of the audion alone used to tune the circuit. For long wave lengths, the distributed capacity of the grid circuit inductance becomes so high with respect to the capacity of the audion that better results are obtained by the use of a tuning condenser to fix definitely the points of maximum potential difference across the grid and filament of the audion.

In the second method of reinforcing the oscillations of the grid circuit the wing circuit of the audion is tuned by means of an inductance introduced as shown by Fig. 9. This differs from the ordinary detector circuit of Fig. 3 by the addition of the coil L_4 and the condenser C_2 . The manner in which the grid oscillations are amplified may best be understood by the following analysis. With no oscillations in the system, the potential difference between filament and wing will be approximately the voltage of the battery B_2 , but when oscillations are set up in the grid circuit, causing radio frequency variations of the wing current, the potential of the wing with respect to the filament varies as the reactance voltage of the wing inductance alternately adds to and subtracts from the voltage of the battery. When a negative capacity charge is placed on the grid, the wing current will be reduced and the direction of the reactance voltage of the wing inductance will therefore be the same as the voltage of the battery B_2 . The reactance voltage will therefore add to the battery voltage and the difference of potential between wing and filament and also between wing and grid will be increased. Similarly when a positive charge is placed on the grid the wing current is increased

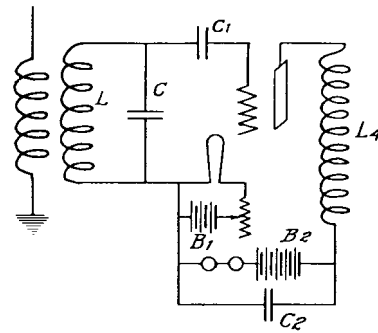


Fig. 9.

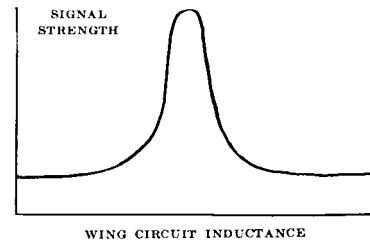


Fig. 10.

and the reactance voltage of the wing inductance opposes the battery voltage, producing a decrease in the potential difference between grid and wing. Hence, supposing a negative capacity charge is placed on the grid, the tendency of the corresponding increase in the potential of the wing with respect to the grid will be to draw more electrons out on the grid, thereby increasing the charge in the condenser formed by the wing and grid, the energy for supplying this charge being drawn from the wing inductance as the wing current decreases. The increased negative charge on the grid tends to produce a still further decrease in the wing current and a further discharge of energy from the wing inductance into the grid circuit. On the other hand, when a positive charge is placed on the grid, the potential difference between grid and wing is reduced and some of the energy stored in the capacity formed by them is given back to the wing inductance. During this part of the cycle, electrons are being drawn into the grid from the surrounding space to charge the grid condenser in accordance with the well known valve action, and this, in effect, is a conduction current, so that a withdrawal of energy from the circuit takes place. In spite of this withdrawal of energy, however, a well defined resonance phenomena between the audion capacity and the wing inductance is to be expected and in the reception of signals such is found to be the case. When the wing inductance is properly adjusted at the resonance frequency, energy from the wing circuit is transferred freely to the grid circuit and oscillations build up therein and are rectified in the usual way.

A curve showing the general relation between signal strength and value of wing inductance is shown in Fig. 10, the circuits used being those of Fig. 9. As the capacity of the audion is the main means of transferring energy from the wing to the grid circuit, best results are obtained when the condenser C is very small. On account of the

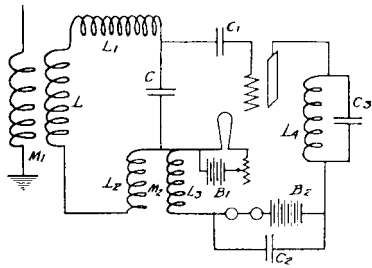


Fig. 11.

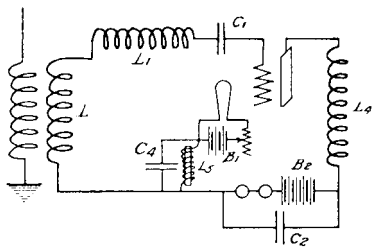


Fig. 12.

very small capacity of the audion, the effectiveness of this method of tuning is more pronounced at the higher frequencies, but by the use of a shunt condenser across the inductance of the wing circuit very good amplification is secured on frequencies as low as 30 000 cycles (10 000 m wave length). The best results, however, are obtained with some combination of coupling and wing circuit tuning, as illustrated in Fig. 11. Other methods of coupling may be employed between the grid and wing circuits, electrostatic and direct magnetic couplings being illustrated in Figs. 12 and 13. The arrangement of Fig. 13 operates in the same way as the system with the two coil coupling; but the electrostatic coupling of Fig. 12 works in an odd way. It is necessary, in this connection, to complete the wing circuit for the continuous current of the battery and this is done by shunting the coupling condenser C_4 by a coil of high inductance. The continuous current of the wing circuit flows through this coil and C_4 provides a path of low impedance around this coil for the radio frequency oscillations of both grid and wing circuits. When a positive charge is placed on the grid, an increase in the wing current results, the alternating component of the wing current charging the condenser C_4 and the sum of the currents passing through C_4 and L_4 equaling the current through the audion. When a negative charge is placed on the grid the current through the audion is reduced and the inductance L_5 discharged into the condenser shunted across it, charging it in the opposite way to that caused by the increase in the wing current. In both cases, C_4 then discharges through the grid circuit reinforcing the oscillations therein.

III. AUDIO FREQUENCY AMPLIFICATION

It is possible to combine with any of these systems a system of audio frequency circuits which amplify the telephone current in exactly the same manner as the radio frequency oscillations are amplified, and such a system is

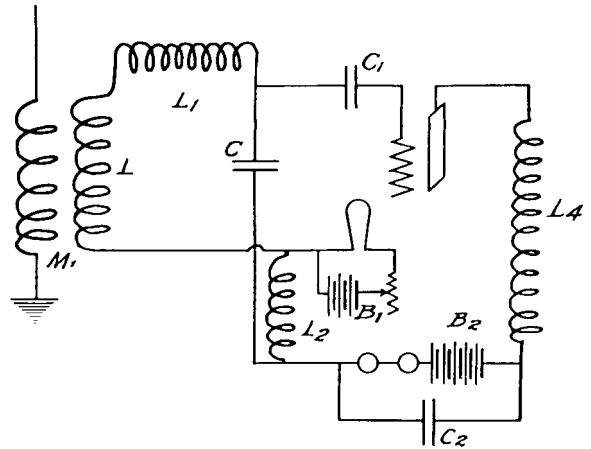


Fig. 13.

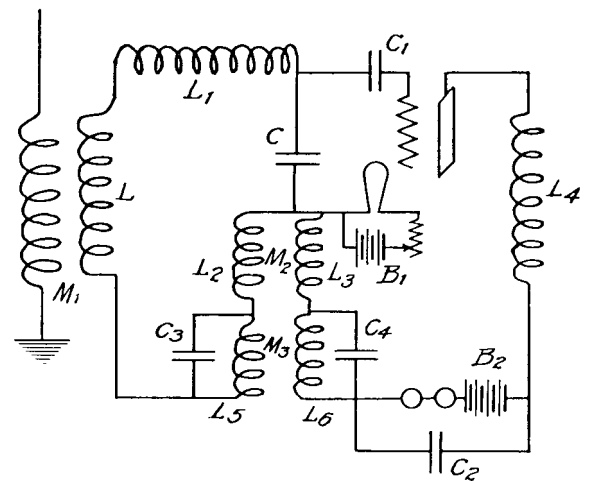


Fig. 14.

shown in Fig. 14. Here M_2 represents the coupling for the radio frequencies and the coils are of relatively small inductance. M_3 is the coupling for the audio frequencies, and the transformer is made up of coils having an inductance of the order of a henry or more. The condensers C_3 and C_4 have the double purpose of tuning M_3 to the audio frequency, and of bypassing the radio frequencies. The total amplification of weak signals by this combination is about 100 times, with the ordinary audion bulb. On stronger signals, the amplification becomes smaller as the limit of the audion's response is reached.

IV. THE AUDION AS A GENERATOR AND BEAT RECEIVER

Any repeater, which is also an energy amplifier, may be used to produce continuous oscillations by transferring part of the energy in the circuit containing the battery back to the controlling circuit to keep the latter continuously excited. By providing a close enough coupling between the grid and wing circuits, sufficient energy is supplied to the grid circuit to keep it in continuous oscillation, and as a consequence thereof oscillations of similar frequency exist in all parts of the system. The frequency of these oscillations is approximately that of the closed grid circuit

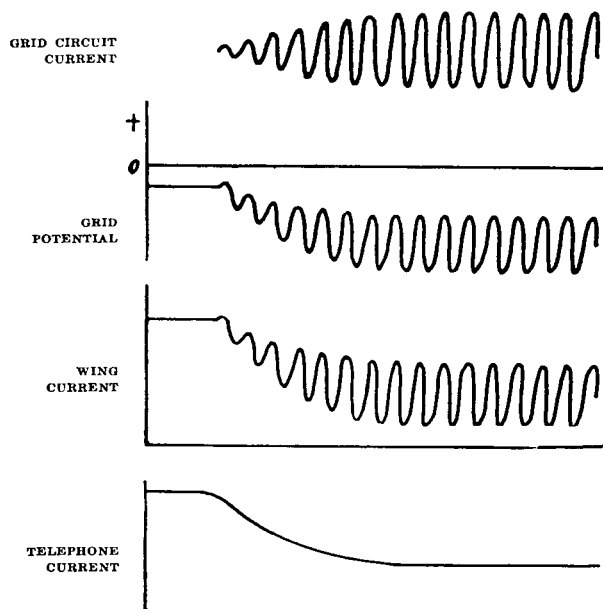


Fig. 15.

if the tuning condenser of that circuit is large with respect to the capacity of the audion. If this capacity is small, then the wing circuit will exert a greater influence on the frequency of the system, and it will not approach that of the grid circuit so closely. When such a system of circuits is in oscillation, it has been found possible not only to receive continuous waves by means of the beat method but also very greatly to amplify them as well.

The phenomena involved may best be understood by reference to Figs. 15 and 16, which show the relation between wing current and time at the beginning of oscillation. When the audion begins generating, the grid oscillations are continuously rectified to charge the grid condenser, and this charge continuously leaks off either by way of the grid or by means of a special high resistance placed in shunt with the condenser. As the negative charge builds up in the grid condenser, it decreases the average value of the continuous current component of the wing current and therefore limits the amplitude of the oscillations of the grid circuit until a point is finally reached where the rate at which electricity is supplied to the grid condenser is just equal to the rate at which it leaks off. Consider now the effect on the system of an incoming continuous wave having a frequency slightly different from the frequency of the local oscillations. The presence of the local oscillations will not in any way interfere with the amplifying powers of the system and the incoming oscillations will build up in exactly the same manner as for the nonoscillating state but to a greater degree because of the closer grid and wing coupling. Simultaneously with the amplifying of the incoming wave, beats are produced between the local and the signaling currents, the effect being alternately to increase and decrease the amplitude of the oscillations in the system. From Fig. 15 it will be apparent that when this steady state is reached an increase in the amplitude of the grid oscillations by any means whatever will increase

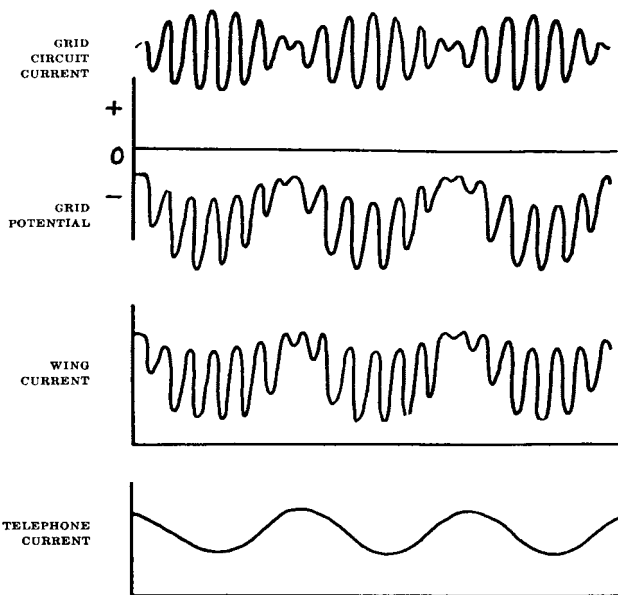


Fig. 16.

the negative charge in the grid condenser, producing a decrease in the average value of the wing current and hence a decrease in the telephone current. On the other hand, a decrease in the amplitude of the oscillations will allow some of the negative charge in the grid condenser to leak off and thereby permit an increase in the telephone current. Hence, when incoming and local oscillations add up, the negative charge in the grid condenser is increased and a decrease in the telephone current results. When the two frequencies are opposed, some of the charge in the grid condenser leaks off and an increase in the telephone current occurs. The result is the production in the telephones of an alternating current having a frequency equal to the difference in the frequencies of the local and incoming oscillations and having the very important property of being almost simple harmonic. Fig. 16 illustrates the characteristics of this method of reception. The complete phenomena may be summed up as follows. Incoming oscillations are simultaneously amplified and combined in the system to produce beats with a local oscillation continuously maintained by the audion. The radio frequency beats are then rectified by the audion to charge the grid and the grid condenser, and this charge varies the electron current to produce an amplifying action on the current in the telephones.

When the grid condenser is omitted, the beat phenomenon is slightly modified, and the audio frequency variation of the telephone current is produced according to the asymmetric action outlined in a previous publication dealing with the operating features of the audion. The system is more sensitive with the grid condenser, but the same general result is obtained by either method of reception.

V. PECULIAR FEATURES OF OSCILLATION

Some very interesting features of operation accompany the production of oscillations in the system. Suppose the audion is not oscillating, and the grid and wing coupling

is fairly weak. As this coupling is increased, the point at which oscillations begin is indicated by a faint click in the telephones accompanied by a slight change in the character of the static. The oscillations produced are usually so high in frequency and constant in amplitude that they are entirely inaudible. As the coupling is still further increased, a rough note is heard in the telephones the pitch decreasing with increase of coupling. This note is produced by the breaking up of the oscillations into groups, and it occurs whenever electricity is supplied to the grid condenser at a greater rate than that at which it can leak off. The result is that the grid is periodically charged to a negative potential sufficient to cut off entirely the wing current, causing a stoppage of the local oscillations until the grid charge leaks off and the wing current reestablishes itself. The frequency of this interruption depends largely on the capacity of the grid condenser, the resistance of its leakage path, and the amplitude of the local oscillations; and it may be varied from several hundred down to one or less per second. This effect is sometimes troublesome in the reception of signals, especially with high vacuum tubes. It may be eliminated, however, by increasing the leak of the grid condenser by means of a high resistance shunt. The best coupling for receiving continuous waves lies somewhere between the point at which oscillations start and the point at which interruption begins, and can only be determined by trial. In this region, trouble is sometimes experienced by the appearance of a smooth musical note in the telephones. This occurs under certain critical conditions of coupling with the antenna when the grid circuit oscillates with two degrees of freedom. Two slightly different frequencies are therefore set up, producing beats which are rectified by the audion in the usual way. This effect is quite critical, and when it causes interference with signals, a slight readjustment of the circuits will usually make it disappear. It may, however, be made perfectly steady and reproduced at will by the system shown in Fig. 17, where two grid circuits of different periods are provided. Two frequencies are therefore generated one having the frequency of the circuit LCL_2 , and the other the frequency of the circuit $L'C'L_2C$. This arrangement may replace to advantage the ordinary buzzer for producing groups of oscillations. The foregoing explanations refer to the audion only when it is used as an electron relay.² When there is an appreciable amount of gas, in the tube in the ionized state, disturbances of an entirely different character occur.

VI. AUDIO FREQUENCY TUNING

One of the very important advantages of the receiver when used for continuous waves is that the alternating current produced in the telephones is almost a pure sine wave. Only when the audio frequency is simple harmonic can selectivity be obtained by tuning the telephone circuit.

²"Electrical World," December 12, 1914; and also discussion in "London Electrician," between Reisz and de Forest on the difference between electron and gas relays. (February 6, 1914, page 726; March 13, 1914, page 956; June 12, 1914, page 402; July 3, 1914, page 538; and July 31, 1914, page 702.—Editor.)

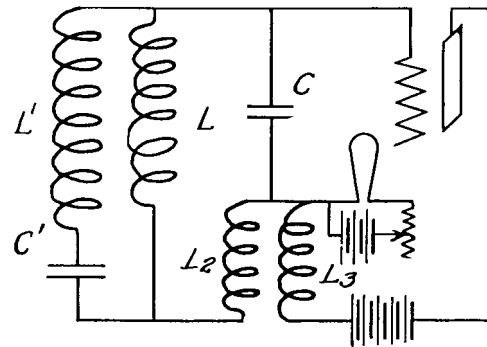


Fig. 17.

A distorted wave such as that produced by spark signals possesses many harmonics and as each may be picked out by the tuned telephone circuit there is little chance of separating two spark signals by audio frequency tuning. With continuous waves, however, the pure wave produced by the beat method of reception makes it possible to obtain selectivity by the audio frequency tuning, resonance being fully as sharp as in the radio frequency circuits. Two methods of audio frequency tuning are shown in Figs. 18 and 19. In Fig. 18, the telephone is inductively connected to the wing circuit of the audion by means of a transformer the secondary of which includes besides the telephone a tuning condenser. In this connection, the telephone, with a resistance of many thousand ohms, is placed directly in the tuned audio frequency circuit, and hence for good tuning the inductance of the coil L_6 must be made extremely large to secure the necessary ratio of the reactance of L_5 to the resistance of the circuit. This disadvantage is overcome in the system of Fig. 19 by removing the telephones from the audio frequency circuit, and using the latter to operate a second audion. The telephones may then be placed in the wing circuit of this audion without adding appreciably to the damping of the circuit. The tuning of the circuit L_6C_6 may therefore be made very sharp with reasonable values of inductance simply by keeping the resistance low. In this case considerable amplification is obtained by the use of resonance in the transformer M_3 to increase the voltage impressed on the grid of the second audion. The great advantage of this kind of tuning is shown by the following example. Suppose the incoming signal has a frequency of 50 000 cycles, and the local frequency is 49 000 cycles. The differential frequency is 1 000, and the audio frequency circuit is tuned accordingly. An interfering wave 1 % shorter than the signaling wave, or 49 500 cycles, will produce an audio frequency of 500 cycles per second, which will not appear at all in the wing circuit of the second audion unless it is many times stronger than the 1 000 cycle signal. This combination of radio and audio frequency tuning is too selective for use at the present time even when the sending station is equipped with an alternator, as the slight changes in frequency of the radiated wave produce changes in the beat frequency of the receiver which carry it out of range for the sharply tuned audio frequency circuit. A disadvantage of this method of tuning is that atmospheric

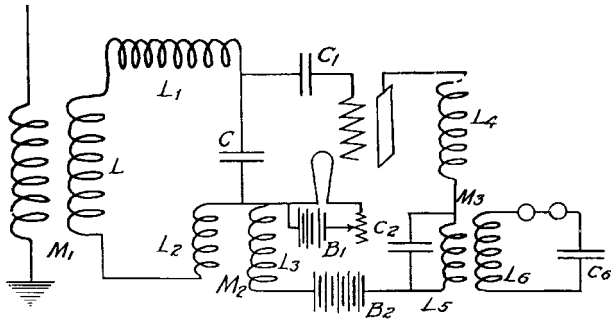


Fig. 18.

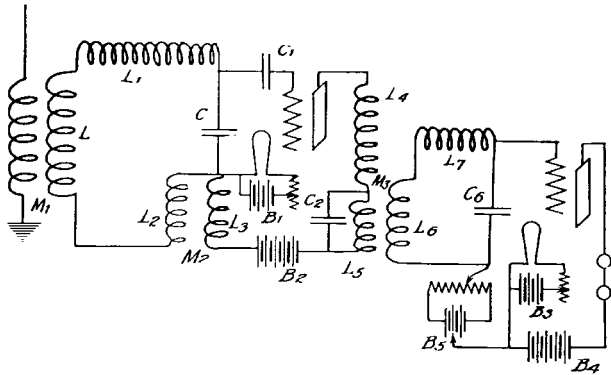


Fig. 19.

disturbances produce a musical note due to shock excitation of the audio frequency system. Very loose coupling with the wing circuit of the first audion is a partial remedy for this. There are times, however, when interference is more troublesome than static and in such cases the method may be used to great advantages. If desired, both radio and audio frequency tuning can be carried out in the same audion as indicated in Fig. 14. This combination is apt to be somewhat troublesome to operate as a cumulative amplification is obtained in the audio frequency as well as in the radio frequency system.

VII. CASCADE SYSTEMS

Where a greater amplification than can be obtained with one audion is required, cascade working of the radio frequency systems may be resorted to by coupling together two or more audion systems, each connected as already described, in the manner indicated in Fig. 19. The incoming oscillations in the first audion system are amplified in the usual manner and set up oscillations in the second system by means of the coupling M_3 (see Fig. 20). The oscillations initially set up in the second system are again amplified, and then rectified in the second audion to produce audible response in the telephones. For the reception of spark signals, considerable adjustment is required to get the best results without causing one or the other or both of the systems to generate oscillations. It will be found that after the first circuit is adjusted to the point of oscillation and the second is coupled with it, the strength of signal in the first system will be reduced owing to the withdrawal of energy

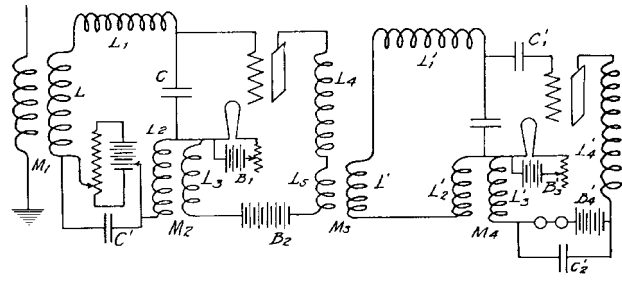


Fig. 20.

from it by the second system. The signals may then be again brought in strength by increasing the coupling between the grid and wing circuits of the first audion until the appearance of the local oscillations indicates that the limit of amplification has been reached. By careful adjustment about a thousand times amplification and very sharp tuning can be obtained with two steps.

For continuous wave reception, there are several methods of operating cascade systems. It is possible to have either system generate oscillations, the other system acting simply as an amplifier or both systems may be made to generate in synchronism. It will generally be found that when both systems produce oscillations, beats will be produced, so that a continuous note is heard in the telephones; but by adjusting the frequency of one of the systems the pitch of this note will be reduced as the two systems approach synchronism, until finally at 100 or 200 beats per second the two systems pull into step in much the same way as two alternators. The ability of the two systems to keep in step depends mainly on the value of the coupling between them, and the closer this is the better the two hold together. There is still another way of working this combination, and that is asynchronously. In this case beats are continuously produced in the system so that a continuous note is heard in the telephone, but the circuits may be so adjusted that the note is not loud enough to be troublesome or it may be tuned out of the telephone in the manner previously described. Incoming oscillations are combined in the system to produce beats with the beats already present so that a rather curious note is heard. Very good amplification is secured by this method though naturally the system is troublesome to operate.

It may be noted here that whenever a signal is too weak to read with one audion system and cascade operation becomes necessary, it is always better practice to use the cascade circuits for the radio frequencies, even if the regenerative circuits are not employed with each individual audion system. The frequency of the oscillations set up in the circuits by static are, under normal conditions, the same as those of the incoming signal; and the static is therefore never amplified more than the signal. Usually it is amplified to a somewhat lesser extent, especially if regenerative circuits are employed. In the cascade systems used for audio frequencies, a different condition exists. It is ordinary practice to connect the different stages by means of transformers, and this leads to conditions which cause

the system to produce greater amplifications of the higher frequencies. The rate of change of the wing current of the detecting audion produced by static corresponds to a very high frequency, and as such is invariably amplified to a greater extent than the signal.

There is a second method of receiving continuous oscillations which makes use of the generating feature of the audion, but does not employ the beat phenomena. The amplifying ratio of the audion depends more or less directly on the value of the wing current, and by varying this current periodically there will be a corresponding periodic change in the amplifying power of the audion. Hence an audion arranged to repeat a continuous wave under such conditions will produce in its wing circuit oscillations which vary periodically in amplitude, and which may therefore be received by a simple audion system. The first audion may be arranged to produce the necessary variation in its amplifying power in the manner indicated in Fig. 21, which also shows the complete circuits for carrying out this method of reception. Here $C_1L_1L_2C_2$ is an audio frequency system designed to produce audio frequency oscillations; and P is a potentiometer for adjusting the potential of the grid so that on the negative part of the oscillation in the wing circuit, the wing current is reduced practically to zero. The radio frequency circuit $C'LCC_1$ is tuned to the oscillation frequency of the incoming wave. The radio frequency oscillations cannot be detected in the first audion system as the strong audio frequency current circulating in this system would produce a continuous note in the telephone receivers of such strength as to render inaudible all save very strong signals. By arranging to detect the oscillations in a second audion system coupled to the wing circuit of the first, interference of this sort is avoided; as the circuit L_4C_4 has a very high impedance for the audio frequency currents and the effect produced through the magnetic coupling of L_3 and L_4 on the second system is negligible. The capacity current between these two coils through the telephones to ground is, however, appreciable; and to avoid it is advisable to ground their two adjacent ends as shown. The action of the system may be summed up as follows. The first audion system varies the amplitude of the incoming radio frequency oscillations at an audio frequency, and the second audion system amplifies and detects the radio frequency oscillations supplied to it by the first system. Diagrammatically, the phenomena occurring are as illustrated in Fig. 22. The system gives about the same response as can be obtained with a single audion working with the beat method of reception. The advantages derived from the heterodyne method of amplification and the dependence of the audio frequency note in the receivers on the wave length are, of course, lacking; but for the reception of waves having a frequency higher than that at which beat reception is practicable, this method is of value.

VIII. EFFECTS OF ATMOSPHERIC DISTURBANCES

A very interesting feature of these receiving systems is their behavior under conditions of severe atmospheric dis-

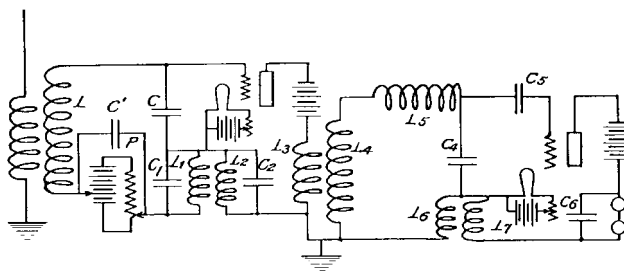


Fig. 21.

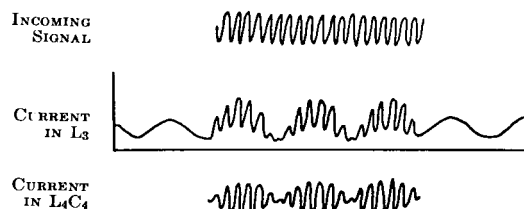


Fig. 22.

turbances, particularly when used for receiving continuous waves. Their success under such conditions is due to the fact that they combine in addition to their inherent property of responding more readily to a sustained wave than to a strongly damped one, the characteristics of the two most effective static eliminators known; the balanced valve and the heterodyne receiver. The function of the balanced valve is a physiological one, as it simply provides a means to shield the ear from the loud crashes which temporarily impair its sensitiveness for the relatively weak signals. In effect, it puts a limit on the noise which can be produced in the telephone by a stray, regardless of its amplitude. Now the effect of the static on an audion is to build up a negative charge on the grid, reducing the wing current, and the limit of the response which can be produced in the telephones is reached when the wing current is reduced to zero. Under ordinary conditions, this limit is too great to do much good; but when the audion is generating it is possible, by proper adjustment of the amplitude of the local oscillations, to reduce the wing current to a point just above the lower bend in the operating characteristic so that the audion is rendered insensitive to a further increase in the negative charge on the grid. The strays which cause serious interference are of a much greater amplitude than the local frequency, so that no appreciable interaction between the two takes place, and the wing current is invariably decreased. Since the decrease in the wing current is not in proportion to the change in the grid potential, the response in the telephone and the effect on the ear of the operator are correspondingly reduced. Static of smaller amplitude than the local oscillations may interact with them to produce either an increase or a decrease in amplitude of the oscillations in the grid circuit and may therefore cause either a decrease or an increase in the wing current. The wing current can, of course, increase to a relatively large value, but as it is impossible for the wing current to increase faster than the charge in the grid condenser can leak off, the rate of increase is necessarily

slow. The response in the telephones is therefore not so disturbing as would be caused by a decrease of similar value where the rate of change of current is usually large.

When the system is operated without an auxiliary leak around the grid condenser, a peculiar paralysis of the audion is frequently caused by heavy static, no sound of any kind being heard in the telephones for a considerable length of time. If the apparatus is not touched, the paralysis may last for many minutes, and then suddenly disappear and the former sensitiveness be restored. The effect is primarily caused by the charging of the grid condenser to a sufficient potential to cut off entirely the flow of electrons to the wing, thereby decreasing the wing current to zero. Now the way in which the negative charge in the grid condenser leaks off is chiefly by means of the positive ions in the tube, which are drawn into contact with the grid when it becomes negatively charged. These positive ions are the result of ionization by impact, and when the voltage of the wing battery is properly adjusted, they can be produced only in the region between the grid and the wing, since the velocity attained by the electrons between the filament and grid is very low. When the grid is charged to a high negative potential it keeps all the electrons between the grid and filament, thereby barring them from the region between grid and wing. Hence the production of positive ions must cease and the usual means of removing the negative charge from the grid vanishes. The resistance of the leakage path of the grid condenser must then be almost infinite, as is shown by the very long time taken for the charge to leak from a condenser of approximately 0.0001 microfarads capacity. The effect is naturally the more pronounced the higher the vacuum, as the number of positive ions present is correspondingly reduced. A resistance of several hundred thousand ohms placed across the grid condenser gives a leak which is independent of the value of the wing current and which effectually prevents trouble of this kind. With the very high vacua now obtainable by the use of a molecular pump, there are practically no positive ions present so that the auxiliary leak is always necessary. Under these conditions, it not only prevents paralysis by the static but it also removes from the grid condenser the excess of negative electricity which accumulates in it, thereby increasing the sensitiveness of the audion and the sharpness of the signals in the telephones. The very high potentials to which the grid condenser may be charged by the static when it is not provided with an auxiliary leak are surprising. These potentials may be measured in a very simple and accurate way, here described. After a stray has cut off the wing current, if we continuously increase the capacity of the grid condenser the potential across it, and hence the potential of the grid, with respect to the filament, will be decreased inversely as the capacity. A point will finally be reached where the grid potential is sufficiently reduced to allow the wing current to flow. When this occurs it indicates that the potential of the grid condenser is slightly less than that shown by the operating characteristic as necessary to reduce the wing current to zero. The potential to which the grid condenser was originally charged is equal to this voltage

times the ratio of the capacity of the condenser at which the wing current began to flow to the original capacity. Voltages of over a hundred are not uncommonly reached by the grid; and as one volt represents a very strong signal, the difficulties of the static problem are very forcibly presented.

The fact that static of large amplitude produces almost invariably a decrease in the wing current while a signal (with beat reception) produces alternately an increase and decrease in the wing current is a circumstance of which it should be possible to take advantage. The circuits can be arranged to rectify the wing current in such a way that only the increases in this current are available to produce a response in the telephones, but in carrying this method out, trouble is experienced from a shifting zero. A better way of making use of the difference in response is the following one. Suppose that we arrange two complete receiving systems oscillating in step with each other, but so related to the antenna that the beat currents in the two systems are 180° apart. The result of this will be that at the instant when the incoming signal is producing an increase of current through the telephones in one receiver, it will be producing a decrease of current through the telephones of the other receiver; so that the two telephone currents are 180° out of phase. Static of large amplitude does not interact with the local frequencies, and will produce simultaneously in each receiver a decrease in the telephone current. These two currents are therefore in phase with each other. On replacing each telephone by the primary of a transformer, and connecting their secondaries through a telephone in the proper phase, it is possible to balance out the static and at the same time secure an additive response of the signals from each receiver.

An arrangement of circuits by means of which this method can be carried out is shown in Fig. 23. Here two oscillating receiving systems are kept in step by means of the circuits $L_1C_1C'_1L'_1$, L_1C_1 and $L'_1C'_1$ are identical, and each is tuned separately to the frequency to be received. When both audions are oscillating in step, the flow of current in these circuits as indicated by the vectors of Fig. 23 will be alternately up on one side and down on the other. The point between the condenser C_1 and C'_1 will be a node; and the antenna may be connected to this point without disturbing the conditions appreciably if a resistance R placed as indicated is included in the antenna. This resistance need not be large enough to interfere seriously with the signal strength; it need only be large with respect to the resistance of the circuit $L_1C_1C'_1L'_1$, which circuit has a very low resistance.

Incoming oscillations pass through the divided circuit as indicated in the diagram, and therefore are in phase with the local oscillations of one receiver and 180° out of phase with the local oscillations of the other. This produces the desired result in the currents through the transformers of the circuit T which act in the manner already described.

It is found in practice that the oscillations set up in each system by the incoming signals tend to neutralize each other through the circuit $L_1C_1C'_1L'_1$. This effect is avoided by introducing in the wing circuits a differential coupling

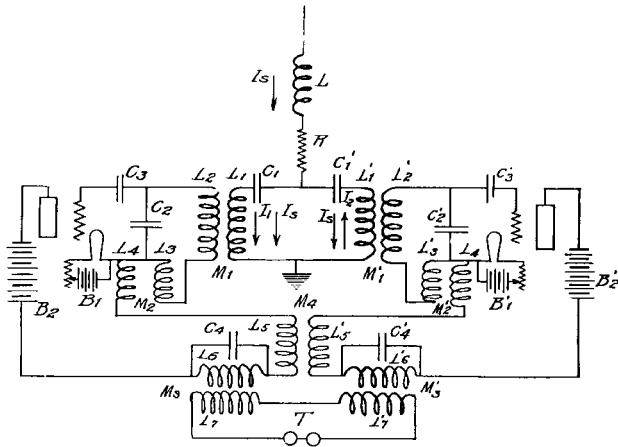


Fig. 23.

arranged to neutralize the coupling between the two grid circuits. It is possible to do this, as it does not affect the coupling of either receiver with the antenna, and does not interfere with the local operation until the effective coupling between the two systems is reduced to a point below which they will no longer remain in step. There are other ways of securing the same result, but the system shown will illustrate the general procedure in carrying out this method of balancing.

The practical results obtainable with these receivers may perhaps be of interest. At the present time, signals from all high power stations from Eilvese, Germany, to Honolulu are heard day and night at Columbia University with a single audion receiver. Cascade systems give correspondingly better results, two stages being sufficient to make the night signals of Honolulu audible throughout the operating room. Interference with the signals from Nauen by the arc station at Newcastle, New Brunswick, Canada, is very easily eliminated by means of an audio frequency tuning circuit; and this is the most severe interference we have yet experienced, the two frequencies sometimes differing by less than 1%, and the arc signals being much the stronger.

These receivers have been developed in the Research Laboratory of Electro-Mechanics, Columbia University; and are mainly the result of a proper understanding and interpretation of the key to the action of the audion; the grid potential-wing current curve. In conclusion, I want to point out that none of the methods of producing amplification or oscillation depend on a critical gas action; they depend solely on the relay action of the tube employed (electron or gas relay) and the proper arrangement of its controlling circuits.

IX. SUMMARY

The action of the audion as a detector and simple amplifier is explained, with the method of verification of the theory by means of oscillograms. To reinforce the oscillations in the grid circuit two methods are employed: first, to couple the grid circuit to the wing circuit and arrange the latter to permit radio frequency currents to pass freely in it; and second, to use a large inductance

in the wing circuit, thereby tuning it to the incoming frequency (in conjunction with the capacity between the filament and wing in the audion itself). Both methods may be used together. Various methods of coupling grid and wing circuits are shown. Methods of combined audio and radio frequency amplification are described.

The audion, being a generator of alternating current of any desired frequency, can be used as a beat receiver. A steady audion generator of regular groups of radio frequency oscillations is illustrated. Various methods of audio frequency tuning permitting high selectivity are possible. By the use of two audions in cascade, amplifications as high as 1000 are attainable. The cascade systems can be arranged so as to operate both audions either synchronously or nonsynchronously.

As an alternative to beat reception of sustained wave signals, an arrangement is explained wherein the amplifying ratio of a repeating audion is varied periodically at an audio frequency. Coupled to this system is a simple audion detector. Musical signals of any desired pitch are thus obtained.

It is found that static of large amplitude nearly always decreases the wing current, while a signal (with beat reception) alternately increases and decreases it. A system of circuits is described whereby this fact is taken advantage of in balancing out static while retaining an additive response to signals, thus effecting an elimination of static to a considerable extent.

Finally, instances of long distance stations received and interference overcome in practice are given.

X. DISCUSSION

Lee de Forest (by letter): Absence from New York and stress of business prevents my giving to Mr. Armstrong's paper the thorough discussion it merits from me.

Briefly, I must state that my investigation of the simple audion detector, the audion amplifier, and the "ultraudion" detector for undamped waves do not bear out completely the results and conclusions announced by that writer.

In the first place, anyone who has had considerable experience with numerous audion bulbs must admit that the behavior of different bulbs varies in many particulars, and to an astonishing degree. The wing potential-wing current curves for different bulbs, or even for the same bulb at different times, under differing conditions (filament temperature, etc.) vary widely.

What may appear to be a fixed law for one bulb may not hold for another.

Mr. Armstrong makes no mention of this well-known fact; nor does he even state that his grid potential-wing current curve may be quite otherwise than he has shown it with different applied "B" battery voltage, or filament temperatures.

He makes no mention of the fact, often demonstrated, that a continuous current indicating instrument, e.g., a microammeter, may show a decrease in deflection, or practically no change in deflection either way when fairly strong radio frequency (or audio frequency) impulses are delivered to the

grid even when the telephone receiver in the wing circuit gives strong response.

I have frequently proven that a *positive* charge applied to the grid, may decrease, rather than increase the "wing current." If I may say so, he treats the entire subject in much too cursory and cavalier a manner, even as he appears to be quite oblivious of the work of any other investigator or discoverer.

As I stated in an article in the *Electrical World*, February 20, the *oscillating* quality of the audion was discovered by me several years ago.

I found that the complicated circuits Mr. Armstrong illustrates were quite unnecessary for producing the effects mentioned. In fact, the combination of oscillating and amplifying functions in the same bulb are obtained almost, if not quite, as efficiently, and far more simply by much simpler circuits.

The second method he shows for a combination tuning to radio and audio frequencies is ingenious and highly creditable. Unfortunately, as he truly points out, there is today no continuous wave generator of sufficiently constant frequency to permit full advantage being taken of this elegant method.

Edwin H. Armstrong: The condition in which a positive potential applied to the grid produces a decrease in the wing current is a remarkable one, in that it has been the cause of that mysterious atmosphere with which the audion has long been surrounded. The effect occurs under certain conditions which are very easily explained. Suppose there is an appreciable amount of gas in the tube and the difference of potential between the wing and filament is adjusted so that a considerable number of positive ions are produced. In such a state it frequently happens that the number of positive ions coming in contact with the grid is in excess of the number of negative ions. As a consequence of this the grid assumes a positive charge with respect to the filament. Suppose the potential to which the grid becomes charged is three volts positive with respect to the negative terminal of the filament. Under these conditions a battery of say one or two volts connected as shown in Fig. 24 with its positive terminal connected to the grid will really change the potential of the grid in the negative sense. The natural result is a decrease in the wing current. The converse of this effect: the condition in which a negative potential applied to the grid produces an increase in the wing current, is invariably met with in high vacuum audions where the potential assumed by the grid is invariably negative. Both cases, however, can be explained on the same grounds. Fig. 25 shows the potential assumed by the grid when a large number of positive ions are present.

Edwin H. Armstrong (by letter): In replying to Dr. de Forest's communication, I want to point out that the paper was intended to deal with the application of circuits of a new type to the actuation of the audion. The fundamental operating features of the audion itself were outlined purely as a basis on which to explain the action of the circuits. A detailed explanation of the various phenomena involved in the audion as a detector and as a relay, radically different

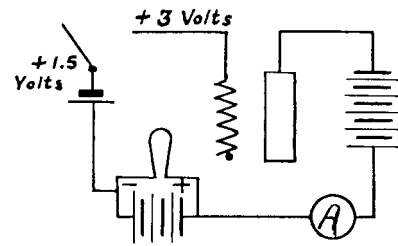


Fig. 24.

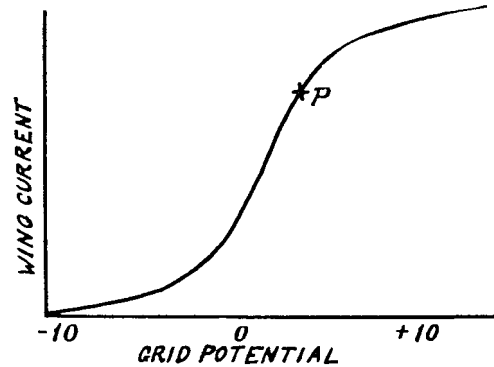


Fig. 25.

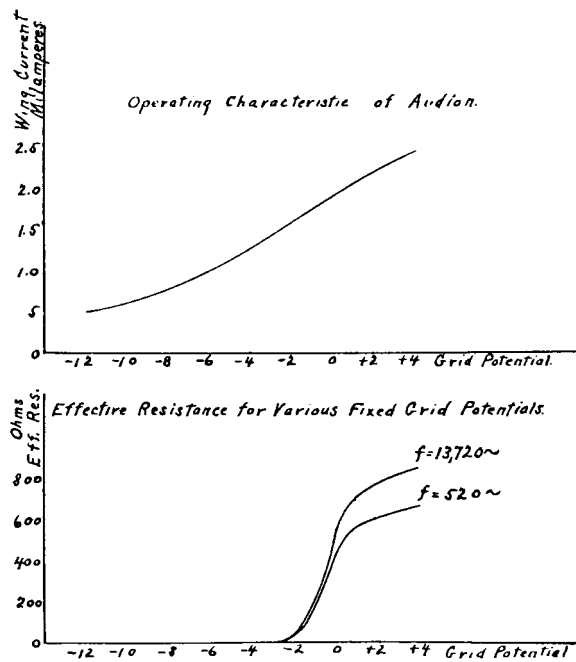


Fig. 26.

from that previously advanced by Dr. de Forest, was published by me some time ago in the *Electrical World*, December 12, 1914, and the columns of that paper, are, no doubt, still open to discussion of these elementary matters.

Dr. de Forest speaks of the great differences existing between the wing potential-wing current curves. It will be readily understood by those familiar with the laws of the conduction of electricity through gases that such is bound to be the case where any considerable amount of gas is present in the bulb. The potential at which progressive ionization

of the gas begins, is dependent, among other things, on the pressure; and hence the upper parts of the wing potential-wing current curves vary, but the lower parts, *the only place where the electron relay can be operated*, are invariably of the same general shape. With the modern methods now available, for producing very high vacua, it is a simple matter to construct audions whose characteristics are for all practical purposes identical. With these high vacuum bulbs, the astonishing differences of which Dr. de Forest speaks disappear to an astonishing extent.

The great differences which sometimes exist between the grid potential-wing current curves of different audions or for the same audion under different conditions of wing potential or filament temperature are again due to the residual gas, and are eliminated as before by the use of very high vacua. It will be evident, of course, that for each value of wing potential and filament temperature there will be a different grid potential-wing current curve; but for high vacuum bulbs these curves lie one above the other in an orderly manner and, barring minor differences, are of the same general shape.

For an explanation of the fact that a continuous current instrument in the wing circuit shows no change in deflection when an alternating EMF of *audio* frequency is impressed on the grid even when a telephone in circuit with the meter gives a strong response, I want to call attention to Figs. 2 and 5, of the original paper, together with a suggestion that a telephone perhaps is apt to respond somewhat more strongly to an alternating current than does a continuous current instrument! An explanation of the decrease of wing current which may occur will be found in the publication in *Electrical World*, December 12, 1914, with an accompanying oscillogram which shows the asymmetric effect in question. The circumstance stated by Dr. de Forest in which a *radio* frequency EMF impressed on the grid produces a response in a telephone but not in a continuous current instrument is an impossible one. If the telephone responded, and there were no changes in the reading of the instrument, it would be an indication of an alternate and equal increase and decrease of the wing current at an audio frequency rate. This is an effect which *radio* frequency oscillations applied to the grid cannot produce. When a condenser is used in connection with the grid, radio frequency oscillations invariably produce a net decrease in the wing current and hence a decrease in the telephone current. Where use is made of the asymmetric relaying, which is possible because of the bends in the operating characteristic, either a net increase or net decrease may be produced in the wing current by radio frequencies applied to the grid, depending at which bend the audion is worked, but an increase and decrease can never be produced at the same time.

Dr. de Forest attempts to throw doubt on the validity of the operating characteristic, and hence on all explanations depending thereon, by stating that he has frequently proven that a positive charge applied to the grid may decrease rather than increase the wing current, a contention originally advanced by him in explanation of the relay and detecting

action of the audion. In the discussion, I have pointed out the fallacy in this view and explained the seeming paradox which is found in low vacuum bulbs on the working part of the grid potential-wing current curve. There is another effect which may lead to incorrect conclusions concerning the action of the electron relay, which is due to effects found above the working part of the curve. As the potential of the grid is increased, it is possible that the wing current may reach a maximum and then fall off. This is due to the fact that a conduction current flows to the grid when it is positive with respect to the filament, and that under certain conditions, this current is subtracted from the wing current. The maximum current which can flow from filament to wing is limited to the number of electrons emitted by the filament, and if the condition of maximum current flow in the wing circuit is established before the grid potential becomes highly positive, then a further increase in the grid potential will increase the number of electrons absorbed by the grid and the result is a decrease in the wing current. The impossibility of working an electron relay on this part of the curve will be evident from the accompanying diagrams (Fig. 26) which show how the effective resistance of the input side of the audion increases as the potential of the grid is varied. Only when the grid is negative with respect to the filament can the full amplifying power of the audion be realized, as the input side consumes no energy. Herein lies the explanation of the great differences which exist in the amplifying powers of different bulbs when used in the customary fashion. It is usual to operate the audio frequency amplifier with the grid insulated from the filament for conduction currents so that the potential of the grid is determined solely by the characteristics of the audion. If it should chance to be sufficiently negative, the input side consumes no energy and the result is a good one; if it should be positive, then the input side consumes energy and the amplification is seriously impaired, the degree depending on the value of the positive charge. All this is clearly supported by the fact that when the potential of the grid of a good bulb is arbitrarily made positive, the amplification falls off. The curves shown in Fig. 26 are additional confirmation, and in this connection it is interesting to note the agreement between the radio and audio frequency curves.

The statement by Dr. de Forest that he originally discovered the oscillating phenomenon and applied it to producing the effects described several years ago cannot be here discussed, because his priority in this matter will be contested shortly in another way.

Lee de Forest (by letter): While I cannot accept Mr. Armstrong's explanations of my observations as to the action of a positively charged grid on the wing current, they have at least more to recommend them than has his previous flat contradiction that such an effect as I have described existed at all.

What Mr. Armstrong states are "elementary matters" have not appeared so to associates and collaborators of Dr. Rutherford and Dr. Soddy with whom I have discussed them. These discussions, however, were prior to the appearance of Mr. Armstrong's paper.

In spite of Mr. Armstrong's explanations, we are left quite in the dark as to how high these consistent vacua are, and just what operating voltages he refers to. More quantitative explicitness and citations of the exact performances of scores of bulb would be more convincing than are the theories proposed as a basis for description of sundry complicated circuits.

If he is dealing with a type of tube which is quite distinct from the audion (on account of the degree of vacuum, the applied potentials, etc.), this should have been explicitly stated at the outset. This is my chief complaint. No essential data are given, but only general laws with attempted axioms. I assumed that we were dealing with phenomena in the audion as popularly known, operating on from 20–50 V. With such, at least, there still remain some unexplained problems.

If he be unable to explain my observation that, using audio frequencies, certain bulbs show a decrease, others no perceptible change in deflection of a direct current micro-ammeter while a telephone receiver gives responses many times audibility—this fact should be frankly stated. I should also like to have his explanation as to why certain audions are distinctly more sensitive to low than to high spark frequencies while others show the exact reverse. Though I have theories on this point, I have not yet proven them.

In connection with Mr. Armstrong's insistence on the value of his oscillograms which were taken at audio frequencies because audio and radio frequency phenomena are identical in nature, I should like to call attention to his statement that "This is an effect which radio (as distinguished from audio) frequency oscillations applied to the grid cannot produce."

Is it not perhaps possible that where successive strongly damped wave trains, of radio frequencies, have alternately positive and negative initial wave fronts, an alternating increase and decrease of wing current may occur which would, while giving loud signals in the telephone receiver, produce practically no change in deflection in a direct current micro-ammeter in series therewith?

As to Mr. Armstrong's closing remark, I had not before realized that he actually claimed broadly the discovery of the oscillating property of the audion. I think it can and will be established that this was discovered some time before his first work in this field. If any are still of the opinion that the oscillating quality of the audion awaited the discovery of the complicated circuits he describes, I would refer them to the article on "The Double Audion Type of Receiver," by Professor A. H. Taylor, in the *Electrical World* of March 13, 1915.

Edwin H. Armstrong (by letter): Replying to Dr. de Forest's latest communication in regard to the effect of a charged grid on the wing current, I cannot but assume, from his failure to produce evidence to the contrary, that his observations may be explained by the residual positive charge on the grid. This applies to the type of tube in which so many "unexplained" phenomena are observed; "the audion, as popularly known, operating on from 20 to 50 V."

Dr. de Forest's misapprehension as to the type of tube referred to in the paper rests entirely with himself. It was definitely stated in the article in *Electrical World*, and on the occasion of the presentation of this paper before the Institute of Radio Engineers that the vacuum of the bulbs was such that only thermionic currents existed. The methods used to obtain these vacua were those recently described by Dr. Irving Langmuir in a paper presented before the American Physical Society, and also in another paper presented before the Institute of Radio Engineers (see this issue of the *Proceedings*, together with the discussion on Dr. Langmuir's paper).

In explanation of Dr. de Forest's observation that audio frequencies applied to the grid may produce either a decrease or no change in the reading of a *direct* current micro-ammeter, while a telephone responds strongly, I have pointed out the oscillograms which fully explain both cases. It seems necessary to add that a *direct* current instrument of the type mentioned measures *average* values!

The question of the relative sensitiveness of an audion as a detector to high and low spark frequencies is entirely irrelevant to the present discussion. It has, however, some points which are of interest. The effect occurs only when the valve action of the audion is used to rectify the oscillations and a condenser is necessarily used in series with the grid. When there is a scarcity of positive ions, the rate of leak of the charge accumulated in the grid condenser from one group of oscillations may be so slow that the condenser fails to clear itself before the arrival of another group of oscillations. Under these conditions, a residual negative charge is continuously maintained in the grid condenser during the periods of signaling, and this charge interferes with the rectifying action between grid and filament. Obviously, this effect will be more pronounced at the higher spark frequencies, and the sensitiveness of the audion will be less impaired on the low spark frequencies. The phenomenon is an interesting one, but on the whole it is quite simple and elementary in character.

Dr. de Forest attempts to explain the circumstance which I have shown is impossible—the circumstance in which radio frequencies applied to the grid produce response in a telephone in the wing circuit but no change in the deflection of a continuous current instrument in series with the telephone. The explanation advanced is impossible. The effect described could be produced only by wave trains that were practically aperiodic. Needless to say, nothing remotely approaching this is in use in radio telegraphy at the present time.

In conclusion, I wish to point out that this discussion was originally begun by Dr. de Forest in an attempt to invalidate the explanations advanced to account for the various detecting, repeating, and oscillating phenomena. It is my opinion that the explanations given stand as correct.

Robert H. Marriott: It has been frequently charged that there has been a lack of research in radio engineering carried out in physical research laboratories. Mr. Armstrong deserves much praise in carrying out this highly interesting investigation, and it is to be hoped that further valuable results will be obtained under similar auspices.

This discussion is herewith closed.—Editor.