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The "Stenode" †

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MIEE, F. Inst. P.

THE Stenode system was conceived as the result of a desire to use the most selective circuits for communication purposes. It has been the constant endeavor of radio engineers and of communication companies to improve selectivity ever since Sir Oliver Lodge introduced the conception of the tuning of circuits. By making circuits more and more selective, it has been possible to increase the number of services which could operate simultaneously and as the tuning of circuits was improved, progress has always been very pronounced as regards freedom from mutual interference, as well as from general disturbances such as atmospherics.

Since radio telephony became prominent, however, it has been considered that no further advantage would be obtained by increasing the selectivity and, in fact, opinion has been universal that it would be incorrect procedure to do so. The application of Fourier's principles to modulation has shown that when continuous waves were modulated by speech or music, the complicated waves can be resolved into a series of continuous waves of different frequencies, there being thus apparently a large number of frequencies transmitted. Thus to receive one telephony service, it was considered necessary to receive frequencies over a comparatively wide band, and in order to be free from distortion, the receiver should be sufficiently flatly tuned to receive all these frequencies uniformly.

Similar views apply to telegraphy, and a state of affairs was reached where wireless services are allocated by international agreement in such a way that the Fourier frequencies or sidebands of neighboring stations should not overlap. Each telephony service should have 10 kc. allocated solely for its own use. A restriction of this nature obviously places a limit on the use to which radio can be put. Under these conditions the time was soon reached when it was impossible to find a convenient frequency band for any new service.

When there is a complicated modulated waveform, as in the case of speech or music, there are many terms of various frequencies up to a maximum of say 5000 cycles per second. The effect can thus be shown as a series of frequencies extending from n– 5000 to n+ 5000. It is to be remembered that this band changes constantly during the performance of orchestras or during any conversations which are employed to modulate the waves of frequency n and thus what are usually called sidebands change as regards the distribution of frequencies and of relative energy in these frequencies, although it can be stated that they are all included in a band whose width is $2p_m$, where p_m is the maximum modulation frequency. It has been assumed, therefore, that as modulated waves can be considered to consist of the transmission of a series of waves extending over a comparatively wide band, it is necessary to receive in an equal manner each of these various frequencies and thus a limit has been placed on the selectivity of receiving circuits. It has been considered essential to have a receiver with a resonance curve which is sensibly flat over this wide range of frequencies, normally 10,000 cycles for broadcasting.

AFTER the presentation of the paper a demonstration of a Stenode receiver was given. The demonstration showed how the Stenode received station WJZ free from interference from two modulated local oscillators. A commercial superheterodyne was also used to receive the same signals and the demonstration showed the difference in reception by the two receivers.

The meeting was then thrown open for discussion and several members of the Radio Club commented on the paper and the demonstration. The discussion lasted about an hour and a half.

A mathematical appendix to the paper will be published in the January issue of the Proceedings together with written discussions on the paper by several members of the Club.

D. E. HARNETT, *Editor.*

Fourier Theories Investigated

It appeared to me to be of importance to investigate whether the generally accepted deductions from the Fourier theories were of universal application in radio and the first aspect to be studied was whether the restriction on selectivity hitherto regarded as indispensable need necessarily apply.

The universally accepted opinion was that if we employ a receiver with a resonance curve whose effective width is smaller than the frequency range of the sidebands, we should be, in popular phraseology, "cutting off the upper sidebands." If a receiver with an effective width less than 100 cycles were employed, the foregoing common expression obviously implied that we should eliminate all the sidebands of music and speech and leave practically only the pure continuous wave component.

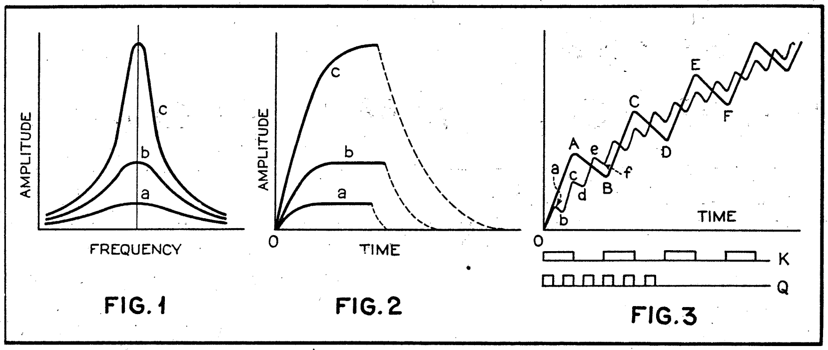
Something was wrong in this generally accepted view, because if one considered a very selective receiver such as one employing a quartz crystal to be acted upon by waves of its own frequency, this crystal would build up to a steady state when the waves were of continuous waveform. It is obvious that if a transmitter were keyed at a very slow rate, we should obtain the complete response of the quartz crystal to the transmission, and if the rate of transmission were one signal per second, we should obtain the rise and fall of the response. If the frequency of signaling increased there would still be change of response, but yet general radio opinion stated that if the signaling speed were at the rate of 5000 signals per second, there would be no change in the response as the upper sidebands would be cut off.

There can be no discontinuity in the nature of the physical response as we go from a signaling speed of one per second to 5000 per second, and it is thus essential to examine the whole phenomenon from an entirely different point of view.

Decrement

Let us consider a resonant circuit which can be obtained in three different conditions as regards the logarithmic decrement, the remaining condi-

† *Presented before the Club, Nov. 12, 1930.*



Figs. 1, 2 and 3. Damping, amplitude and response curves, respectively.

tions being constant. Fig. 1 shows resonance curves for these three conditions, the resonance curve a relating to the case of the highest damping and c to that of the lowest damping. We shall examine these conditions by plotting the rate of rise of the oscillations which arrive at the circuits. This is shown in Fig. 2 where we plot the amplitude of the oscillations in the circuit against the time when continuous waves arrive. We find that for the curve a the oscillations build up to a comparatively low steady state, whereas in the case of low damping, c, a large steady state is finally obtained. The amplitude of the steady state in fact is inversely proportional to the resistance in the circuit.

Another very important fact emerges from these curves which is that although the curve c eventually reaches a higher amplitude than that of curve a longer time is required for it to reach its steady state. In each case here we are considering the waves which arrive to be in tune with the receiver. When the incoming waves cease, the receiver is in a state of oscillation and these oscillations will commence to die away at a rate depending on the logarithmic decrement. In each case we have an exponential fall of the oscillations and for the case of high damping the receiver comes very quickly to rest, whereas for the case of low damping (curve c) a considerable length of time is required for the receiver to come to rest.

Suppose that we make a signal at a transmitter and that we wish the receiver to respond to its full extent and to die down to zero again, it is obvious from these curves that the length of the signal which we can use depends on which of the curves a, b or c, we employ. In the case of curve a, a comparatively short time is required to build to the maximum value and a comparatively short time to die down to rest again, whereas in the case of curve c, a very much longer time is required for the receiver to build up to its maximum value and to die down to rest again. Hence if we make the condition that the receiver must always be allowed to rise to a maximum value and must always come to rest again for any one signal, we arrive at the conclusion that the lower the damping of our receiving circuit, the lower must be the signaling speed of the transmitter.

High Signaling Speed

Let us now examine what would happen if we actually do employ very high signaling speeds for these circuits of exceedingly low damping. In Fig. 3 we again plot the amplitude of response of a very selective circuit against the time, and the actual response of such a receiver to telegraphic signals of two different speeds is also shown.

First of all, we shall consider signals as shown at K and we must assume that these signals are made so that the transmitter is active and at rest for equal intervals. For the first active portion, the amplitude of oscillation will build up to the point A. When the incoming waves cease, these oscillations will tend to die away, and as a comparatively long time is required for this process, it is obvious that we cannot afford to ignore the exponential effect, which in fact becomes of very great importance. In the period of rest, however, the receiver will only die away to the point B and it will still be in a state of oscillation when the next signal arrives. This will now (provided we arrange for it to start in the correct phase) build to the amplitude of oscillation of the point C, when the signals again cease. Again, the amplitude falls to the point D in the period of rest when the signals again arrive.

Thus for the signals K we find that the receiver continues to build up according to the curve OABCD, finally reaching a steady state with the amplitude varying according to the signals.

Consider now that the signaling speed is increased as shown at Q. The build up curve becomes oabcd, again the amplitude building up to a steady state with a fluctuation, the rate of fluctuation corresponding to the signaling speed but the amplitude of the fluctuation being smaller than in the case where the signaling speed was lower.

Fig. 3 is sufficient to show that no matter what telegraphic signaling speed is employed, provided that this is lower than the frequency of the carrier waves, we shall have the amplitude of the receiver fluctuating with the signals, the amount of fluctuation depending on the signaling speed.

In place of telegraphic signals as shown at K and Q, it is obvious that we could employ signals of trigonometrical form, instead of being square-topped as shown at K and Q. Similar reasoning will apply, and this means that instead of transmitting telegraphic signals of square-topped form, we are transmitting signals of trigonometrical form which, in fact, are equivalent to a trigonometrical modulation of the carrier waves. Thus we find that when the carrier waves are modulated by any frequency, we have the amplitude of oscillation fluctuating at the same rate as the modulation, but the amount of the fluctuation depends on the modulation frequency, being greater for a lower modulation frequency.

The important deduction to be drawn is that in this very selective circuit, all modulation frequencies, or all signaling frequencies are present, although not in their original proportions. We can, in fact, deduce a general principle, which is that when modulated waves impinge on a receiver, the percentage modulation is changed after going through the receiver to an amount which depends upon the logarithmic decrement and also on the modulation frequency. Thus no matter how selective we make a circuit, all modulation frequencies are still present, although they are not necessarily present in their original relative intensities. For extreme selectivity it was apparent that the response of any signaling frequency would be approximately, if not exactly, inversely proportional to the signaling frequency.

The Receiver

Having reached this very important deduction, the way was shown to the construction of a suitable receiver, by employing a very selective device and arranging for the correction of the modulation frequencies so that they should appear in their desired proportions. For instance, one method for bringing this about is to pass the modulated waves through a highly selective circuit, such as a quartz piezo-electric crystal, then to rectify the effects and pass the result through a low-frequency amplifier which has the characteristic of amplifying the frequencies so that the amplification factor is proportional to the frequency.

Thus it is seen that there is no necessity to place a limit on the selectivity of a circuit.

Magnitude of Modulation Response

The conclusion that has just been arrived at that the percentage modulation is reduced as the selectivity increases, helps us to appreciate that the magnitude of the modulated response is not small. Although the percentage modulation has been diminished, the total response of the circuit at resonance has increased as some resistance has been cut out of the resonant circuit to produce the selectivity. Hence although the percentage modulation is diminished, the absolute value of the modulation is not necessarily lowered.

Examining the curves of Fig. 2 it can be seen that the absolute magnitude of the modulations is in fact not smaller for the highly selective circuit c than for the damped circuit a. In each case the amplitude builds up to a steady state where the input of energy into the circuit just balances the dissipation of energy. For curve c, the rate of input of energy is given by the tangent of the angle AOT, Fig. 4. This angle gives the rate of loss of energy at the point P, and thus when the input of energy ceases, the energy will fall away along a line PQ where the angle QPK=AOT.

The modulated signal is given by the amount of fall from the point P, and in a given small interval it will fall through PK, which equals the amount of rise of amplitude which we would obtain in this circuit when starting from rest. Obviously this is greater for the selective than for the non-selective circuit.

We thus have the following results:

1. No matter how selective a circuit may be, all modulation frequencies are present.

2. From a quantitative point of view the signals need not be weaker than they are in a highly damped receiver.

3. We can now employ selectivity as high as is practically possible and there is no need to place a limit to progress as regards selectivity. We should expect that as the selectivity is improved, such annoying factors as spark and atmospheric interference should be diminished.

4. The percentage modulation of waves is changed after they pass through a very selective device by a factor which is approximately proportional to the logarithmic decrement and approximately inversely proportional to the modulation frequency.

Practical Methods

Having established the fact that no matter how selective a receiver may be, it is still possible to receive all modulation frequencies, we shall consider certain practical methods for utilizing these principles in radio.

Highly Selective Receiver with Equalizing Amplifier

It is known that when a quartz crystal is cut in a special manner it has a definite frequency and that it can be employed as a resonater. Professor Cady has shown that when such a quartz crystal is connected in parallel across a resonating circuit, and when the resonance curve is plotted, the normal curve is obtained with the exception that at a very definite frequency a crevasse M appears in the resonance curve as shown at Fig. 5. This crevasse M occurs because at or near this very definite frequency some of the oscillating energy is constrained to pass through the crystal.

Such a resonator is obviously very selective and our object is to employ it not in the form of a crevasse in another resonance curve but merely as a resonator of its own accord. We thus need to obtain our indications actually in the quartz crystal circuit itself and for this purpose the crystal is connected between one end of the resonance circuit and the grid of a tube of Fig. 6. The crystal is shown as Q. Such an entirely new departure in radio reception brings forward a number of peculiar problems, one of them being the fact that it is usually necessary with the crystal to employ electrodes or plates, thus providing a capacity which is capable of passing high-frequency energy. It is necessary to correct any such effect, and one method of doing so is to employ a small condenser C connected to the opposite end of the resonating inductance, the filament of the tube being connected to a center point of the inductance.

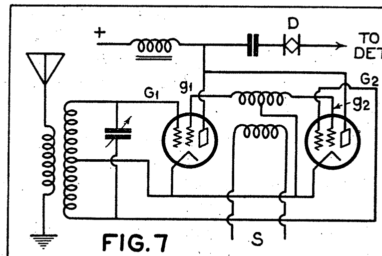
Thus in effect we provide a bridge circuit by means of which undesirable effects of any capacity of the quartz mount can be compensated. Effective reception with such a crystal obviously only occurs for a narrow frequency band and thus in order to employ one such crystal for a range of frequencies it is suitable to employ the supersonic principle, in order that incoming waves can have their frequency changed to that of the crystal.

It is not essential to describe in detail these supersonic portions of such a receiver, as this principle is well known. Following the quartz crystal, rectification is effected, after which a low frequency amplifier is used which is designed to amplify in proportion to the frequency.

Certain special features of rectification are introduced because the percentage modulation is low, although the actual amount of modulation may be quite normal.

Reversal of Phase Method

Another interesting method of employing a highly selective device in a different manner in order to obtain complete modulation frequencies is as follows: Referring to Fig. 2 it is seen that with such a selective device a considerable interval of time is required for the receiver to build up to its maximum amplitude, and at the same time this maximum amplitude is very high. It is, however, not



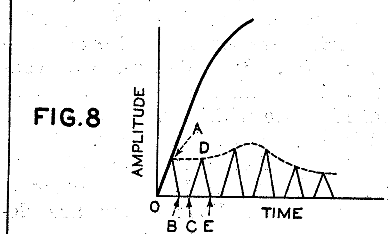
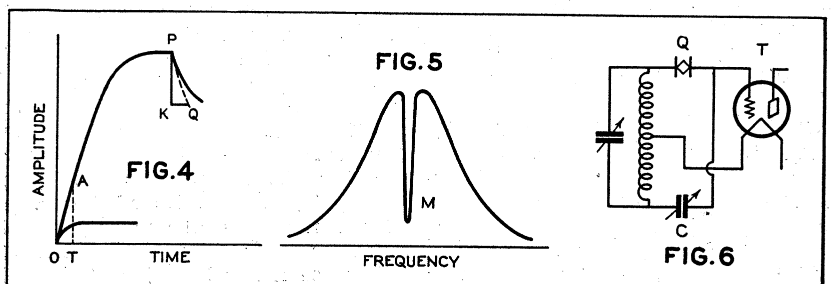


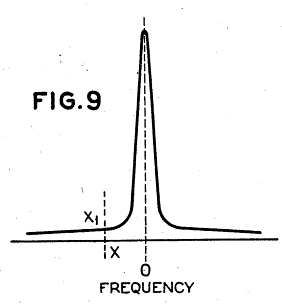
Fig. 7. Incoming signals led to two tubes. Fig. 8. Selectivity—does not affect modulation frequencies.

necessary to allow the receiver to reach its maximum amplitude and after a short interval of time when the receiver has built up to a comparatively small value, it is possible to bring it to rest again. This can be done by reversing the phase of the incoming signal. To show how this can be done a diagram is given in Fig. 7, a description of which appeared in *The Wireless World*, London, of December 11, 1929. In this case, incoming signals are led in opposite phase to the grids g_1 and g_2 of two tubes which are made alternately active at a lower frequency which would normally be supersonic when telephony is being received, by leading an alternating voltage of this lower frequency from a source S, Fig. 7 to second grids g_1 and g_2 in the two tubes.

In this way in the combined anode circuit of the two valves we obtain trains of waves with opposite high frequency phases in the successive trains which are led to the highly selective device D. We thus obtain a series of pulses as shown in Fig. 8. OAB, CDE, etc. The amplitudes of these pulses depend on the instantaneous intensity of the incoming waves. After rectification the envelope of these pulses corresponds to the form of the low-frequency waves, so that such a



Figs. 4, 5 and 6. Curves illustrating energy transfer.



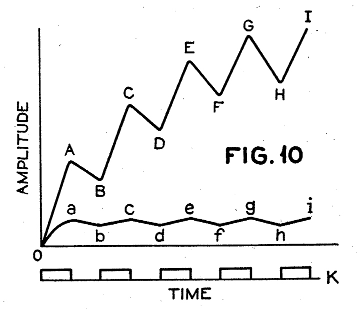


Fig. 9. Typical resonance curve of highly selective circuit.

Fig. 10. Telegraph signal impulses.

receiver although exceedingly selective will still indicate all the modulation frequencies.

Interference with the Stenode

Once it has been appreciated that all modulation frequencies are present in a receiver of this nature no matter how selective it may be, certain deductions can be made.

The opinion has been universally held that the ideal receiver for broadcasting reception should be able to receive equally waves over a frequency band of ten kilocycles and receivers have been designed employing band-pass filters to eliminate waves whose frequencies are outside of such frequency band. Such designs have concentrated on methods for obtaining equal response within the required frequency band of ten kilocycles.

In this connection it is important to point out that when the high frequency circuits of a radio receiver are designed to respond to a wide band of frequencies, such as, 5000 cycles, either side of the carrier frequency, there is an inevitable loss of the efficiency which comes from utilizing the principle of resonance to its best advantage.

One important result of the work on the Stenode system is the advancing of a definite group of principles hitherto entirely unrecognized, which may be employed by the application of sound engineering to bring about results considered up to now as entirely impossible.

Interference

It is now necessary to consider in what manner interference will be caused by waves of frequencies different from that to which the selective receiver is tuned.

We must consider what will happen if the interfering frequency is nearer than ten kilocycles. The general conception of the sideband theory appears to be that when the carrier frequency is nearer than ten kilocycles, interference should be experienced.

A general discussion on the nature of sidebands took place in the pages of *Nature* early in 1930, and various scientists, particularly Fortescue and Glazebrook recalled the fact that simple modulated waves, i.e., waves of frequency n modulated at frequency p do actually give resonant response in a receiver at the three frequencies n, n+p and n—p. Because of this it might be considered that if the interfering carrier frequency is 1000 cycles away and has a modulation of 1000 cycles, one of the sidebands so produced will fall directly on the resonance curve of our receiver and will thus produce considerable interference.

While there is no doubt that under such conditions the receiver would be excited, no interference is actually produced because this interfering sideband is purely of continuous wave-form and it will operate in conjunction with the desired carrier wave to determine the maximum amount of build up in the receiver. The preceding discussion has shown that the desired signals are the variations of this maximum build up.

The probability that we should obtain an interfering station with a prolonged note of such frequency that it produces a sideband accurately on the resonance curve of the receiver is very small with the Stenode and this probability diminishes as the selectivity of the receiver is increased.

A more general case is that the interfering station will have a modulation frequency of variable intensity which produces a sideband accurately on the resonance curve of the receiver and in this case intensity of this sideband is very much lower than when one constant note is being produced. The variation of intensity in this case is at a very slow rate being controlled by the speed of manipulation of musicians and is thus at a rate of the order of one per second.

We must thus look to other causes for any possible interference and we shall now consider what interference is obtained from the carrier wave of a neighboring station. Fig. 9 may be taken as a typical resonance curve of a highly selective circuit, and it is seen that an adjacent station at X will produce an effect on the selective receiver even though this effect is small. In most of the experiments up to date, it is found that such a carrier does produce a small interference and, although this does not form part of the present paper, means can be employed to remove this interference.

For the moment, however, we shall discuss the nature of this small interference of a carrier frequency. Let us consider the build up effects that are obtained in our selective receiver by an interfering station at X in a similar manner to that in Fig. 2.

In the first place, if the interfering station is of continuous waveform of frequency n, we have the build up of the signals as shown at oaceg, whereas for a signal of the same intensity actually in tune, i.e., of frequency n_0, the build up for continuous waves is OACEG. Let us now consider that we modulate the signals and employ telegraphic signals as shown at K Fig. 10. For the interfering station we have a low maximum value for the amplitude. Consider the case at the point e when a signal has just ceased. We have here the case of forced oscillations which have built up a small amplitude. At the time given by e the receiver is actually being forced to oscillate at a frequency n_2, which is different from the natural frequency of the circuit n_0. When the input of energy ceases, the receiver will continue to oscillate in its own natural frequency n_0 and the oscillations will die away according to an exponential curve determined by the damping of the oscillating circuit.

As the initial amplitude of the oscillation at e is small and as the damping is minute, we shall have the receiver dying away to the point f in the spacing interval, when there is no incoming energy. This exponential curve is of the same family of exponential curves as that given at EF and the slope of ef is further, very much lower than that of EF.

When the next signal arrives at e the receiver will build up to the point g (provided that the phase of the incoming signal is correct) and the total result is that the incoming signals give a maximum oscillation which is small, with a variation of amplitude which is still smaller. Thus the interfering station, when of continuous waveform produces energy given by oaceg and when this interfering station is modulated, we still have this same energy with a small variation of amplitude corresponding to the signals, i.e., oabcdefg. In fact, qualitatively, it is apparent that the percentage modulation of the interfering signals is of the same order as that for the signal which is in tune with the receiver.

The result has thus been obtained that when we have waves of a frequency n_0 modulated by speech, music or the like, and when we employ a very selective receiver, the modulation response is a maximum when the receiver is tuned accurately to the frequency of the incoming waves and that this response rapidly diminishes as the receiver is progressively detuned from this frequency. By making a receiver of the highest possible selectivity, the modulation response of a transmission whose frequency is less than 5,000 cycles away from that of the receiver can be made negligible.

This result is in accordance with our earlier conceptions of tuning, but at first sight, it appears to be a contradiction of the sideband theory. This latter theory is an application of the Fourier analysis to radio, and in consequence it has been considered to be a correct interpretation of all facts of modulation.

It is, however, very significant that there are certain phases of radio analysis where it is customary to employ the actual modulated waves instead of the Fourier components, such as for instance in problems of rectification, and it begins to be a case for consideration, whether the sideband theory as at present formulated, being merely a statement of Fourier's analysis, gives a complete statement of the case.

The case has not been completely analysed so long as problems of rectification and detection have been omitted. Then again it must be remembered that the Fourier components are changing in amplitude and frequency for the general case of modulation, such as for speech, music, telegraphic signals or television. Another consideration is that the Fourier analysis gives values for the amplitudes, frequencies and phases of the various components, and the question of phase shows that we cannot apply simple arithmetical addition to these various components.

This becomes of great importance in the case of the Stenode where the receiver is exceedingly selective. Still another factor which must be considered in the case of the Stenode is that we must take into account free oscillations which are given by the exponential term in the solution of the basic differential equation for oscillating circuits. With ordinary receivers, it is usually unnecessary to consider the exponential term as it is of small importance, but with the Stenode it cannot be ignored.

There is one other very important consideration in connection with the exponential term. The effect of this term is large in the Stenode and it is not easy to subject it to mathematical computation. Its value at any instant depends on the actual amplitude of oscillation in the selective circuit and as this amplitude is changing for modulated waves the value of the exponential term is also changing. When one attempts to apply the sideband analysis to the Stenode, the question arises as to the vectorial addition of various sideband effects. Such addition is permissible provided that each term is entirely independent of the other terms but when the exponential term is of large importance the sideband effects are not independent of each other and thus simple addition cannot be applied.

These considerations show that the application of the Fourier analysis to the complete radio equipment is not quite simple, and that when new facts are brought forward as in the present case of the Stenode, the application of the Fourier analysis must be made in a manner to include the whole of the phenomena.

Summary

The Stenode system is a departure from hitherto universal practice, where it was considered necessary to employ a widely tuned receiver in order to receive all the sidebands of the transmitting station. In fact, the Stenode system makes it possible to increase selectivity to the utmost practical limit and still obtain all modulation frequencies. While employing selectivity of a much higher order than normal it is possible to obtain all modulation frequencies and to apply a low frequency amplifier which may be designed according to a clearly defined law that the amplification factor is proportional to the frequency and thus to obtain fidelity. Another result arrived at is that there is a large improvement possible in the ratio of signal to interference whether the latter may be from natural or other causes. From a quantitative point of view, the signals are at least as strong as they are in the normal highly damped receiver. Some of the effects of the Stenode system can be expressed in the form that the percentage modulation of waves is changed after the waves pass through a selective device by a factor which is proportional to the logarthmic decrement and inversely proportional to the modulation frequency. It further brings out the possibility that modulated stations can be placed considerably closer than 10 kilocycles apart without interference and with perfect fidelity.

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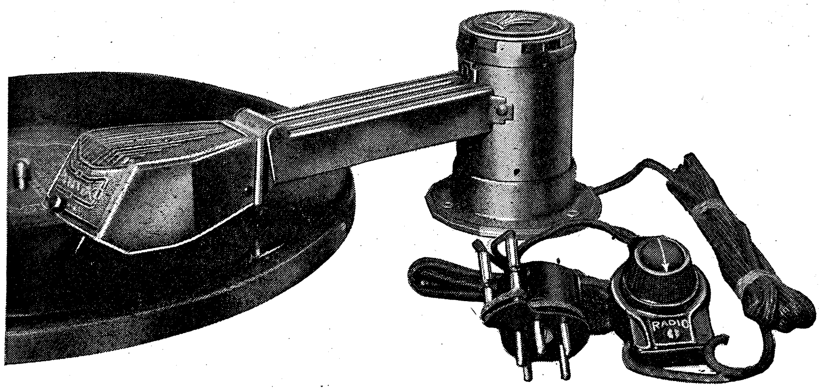

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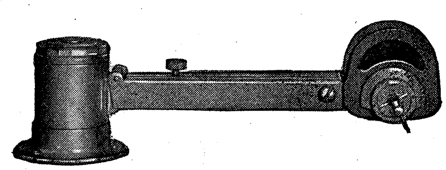

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