Amplitude Range Control

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The art of controlling the amplitude range of telephone signals involves recognition of certain characteristics in addition to those used to specify the performance of ordinary transducers. Fundamentally, three kinds of characteristics are necessary to distinguish different range control devices. They are (1) the steady-state input-output characteristics, (2) the time actions, and (3) the range over which they function. In some cases, several secondary characteristics may be of interest, but they need not be considered in determining to which class a particular device belongs.

This paper discusses and classifies these characteristics.

Introduction

IN a "non-linear" transducer, the output power is not proportional to the input power. Consequently, the ratio of maximum to minimum power at the output differs from that at the input. But the ratio of maximum to minimum power is an expression of amplitude range. A device designed to alter this ratio may be called a *range controller*.

In telephony the term *range controller* includes many devices [1] having specific names, such as limiters, volume control devices, range reducers, compressors, vogads, expandors, etc. These devices have many properties in common with telephone repeaters, and a repeater may be considered as a special case in which any non-linearity which may exist between the output and input is unintentional.

The purpose of one type of range controller is to reduce the range of significant intensities of signals applied to a telephone circuit so as to ease the requirements of the transmission medium with respect to overloading and noise interference. Such a device is placed at the transmitting end of the circuit. When the range is compressed at the sending end of the circuit it may sometimes be desirable to expand it at the receiving end to the original range. This is done with a device having, in general, the same dynamic characteristic as the compressing device, but a range change which is complementary. The purpose of the expandor is to reduce the noise heard by the listener as well as to compensate for whatever characteristic signal modification occurred in

[1] For numbered references, see end of text.

the process of compressing the original wave. Sometimes an expandor is used at the receiving end to reduce the gain in the intervals between the main signals even when no compressor is employed. This is an example of using a range controller to correct defects in the medium.

As is well known, the performance of a repeater is specified by such characteristics as impedance, amplification, frequency band, noise, and output carrying capacity. The performance of a non-linear device involves some additional characteristics. The primary ones are (1) the slope of the input-output curve, which tells how the range is changed, (2) the dynamic operation, which tells the manner in which the output varies with time following a given change in input, and (3) the range, which tells the region over which the device exercises control.

It may be helpful to imagine a range controller as an amplifier in tandem with an adjustable attenuator, the loss of which may be changed either instantly or slowly to follow in some predetermined fashion changes in the signal. For simultaneous operation, this device could put out a wave which is a simple function of the input, but if the operation were delayed by a definite interval the device would be required to respond in a complex fashion in accordance with a recollection of what had occurred in the signal during the delay period. Such delayed adjustment would be very crude for intervals comparable with the periods of fundamental speech frequencies. To obtain practical regulation of the delayed type it is necessary to increase the delay beyond this range and base the control upon the amplitudes of the syllables. When the delay is increased to a point where it is comparable with the syllabic periods its usefulness is again reduced.

PART 1—CONTROL RATIO

Fundamental Characteristics

Figure 1 shows how waves may be altered by a device having a given output-input characteristic, assuming the operation is instantaneous. As this figure is plotted on a db scale, only the stronger portions of positive values of the wave are shown. A similar diagram could be drawn for negative values. The output-input characteristic, although a straight line in this kind of diagram, would of course be parabola-like if plotted on a current or voltage basis. By selecting points, such as A (or B), on the input wave and determining the relative outputs A'' (or B''), the corresponding resultant wave is obtained. In this case, the resultant has a flatter top than the original sine wave, and this illustrates the capabilities of the device in increasing weak signals with respect to the strong ones and also suggests that distortion may accompany the transformation. Such effects depend upon the slope of the output-input characteristic.

The control ratio of a range controller might be defined as the output range in db divided by the input range in db within the non-linear region of interest. The ratio is obtained in such a way as to eliminate transient effects, i.e., using steady-state sine waves.

Typical Control Ratios

Figure 2 shows some typical output-input characteristics for various transducers having control ratios between zero and infinity. While

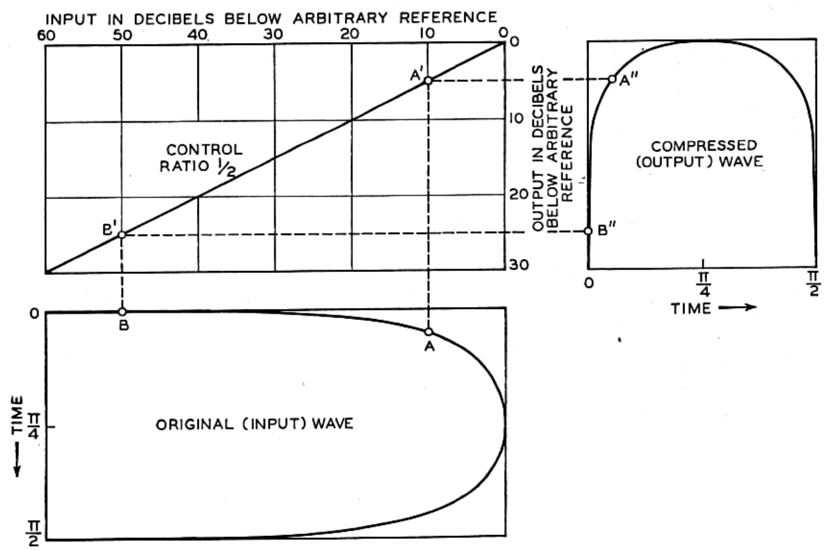

Fig. 1—The signal modification caused by a non-linear transducer depends upon the slope of the output-input characteristic.

these typical characteristics are straight lines there is nothing to prevent a range controller having a control ratio which varies with input. However, when complementary action is required at the receiving end it is more readily obtained when the control ratio is constant. Also, some physical elements used in the design of range controllers are most readily adapted to a straight line characteristic.

Compressors (that is, devices having control ratios less than 1) may be divided into two classes: (1) Complete * and (2) Incomplete. In a complete compressor (control ratio = 0) the output is held constant within the range of the device. This control ratio gives a maximum

* This is not usually of practical interest but is useful as an ideal limit of operation.

of possible noise improvement and also a maximum of signal modification. There is, however, no information in the compressed signal

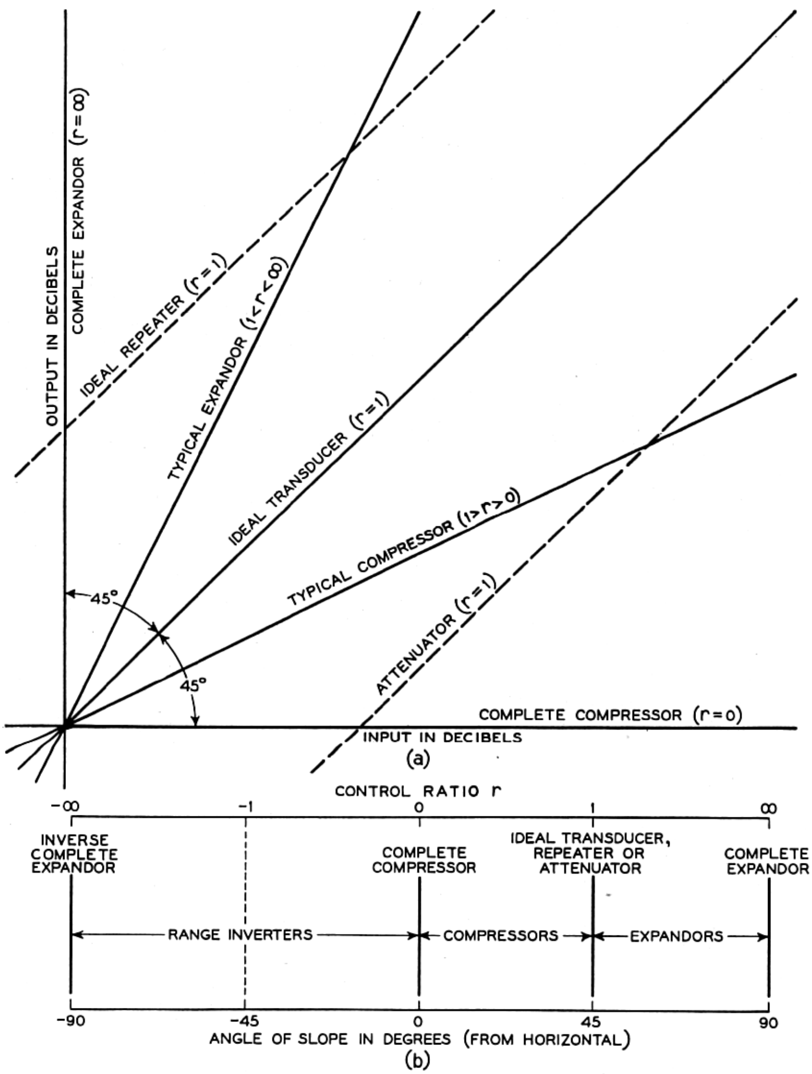

Fig. 2—If transducers are classified with respect to the slope of the input-output characteristics, several fields of action with definite demarcations result.

which would serve to indicate how much compression occurred. Consequently, if it were desired to restore the original range, it would be necessary to transmit this information in addition to the compressed signal. The gain of the restoring device would be guided by this auxiliary information. Hence, the device used to pass the information along is called a "pilot channel." Various types of pilot channels are listed in Part 4 as secondary characteristics of the control.

When the control ratio is between 0 and 1 the compression is incomplete. A wave compressed in this manner has the property of being able to cause re-expansion at the receiving end since the output amplitude bears a definite relation to the original, assuming constant transmission over the intermediate circuit.

In the field of expandors having a control ratio between one and infinity the signal modification is opposite to that of compressors. Thus a convenient method is available for restoring the original wave shape by using an expandor having a control ratio which is the reciprocal of that of the compressor at the sending end.

Effects of Control Ratio

The control ratio is useful in determining the effectiveness of a device in improving transmission in the presence of noise in the medium. When noise alone is acting on the device, the noise determines the action in a manner similar to speech. When both noise and speech are present, the action is determined by the sum of the two. Thus, room noise applied with the speech will be compressed or expanded exactly as if it were part of the speech. In the case of a compressor used at the sending end of a noisy circuit, an input range of say 60 db might be compressed to 20 db, by using a control ratio of 1/3 over the entire input range. At a point where the strongest signals are unchanged, the weaker signals would then be 40 db stronger than when the compressor was omitted. The improvement of the signal and applied noise with respect to noise in the medium thus depends on the difference in ranges at the input and output which depends on the control ratio.

A large part of the usefulness of an expandor is in changing the apparent ratio of speech to the noise heard in the absence of speech, since the noise is generally weaker than speech and is made even less compared to speech by expansion. This is in spite of the fact that at any instant the signal-to-noise ratio is the same at the output as at the input. When the noise is comparable with the speech in amplitude, or when the noise is so weak as to be negligible without a controller, there can be no improvement in the noise conditions in using these devices. Between these two limits, the noise improvement rises to a maximum value also determined by the control ratio, and the time actions and range to be discussed.

A receiving range controller also changes variations in the transmission medium in proportion to the control ratio.

Part 2—Time Actions

Instantaneous Control

A device having a given control ratio might have its gain changed simultaneously with the applied e.m.f. The signal modification would become greater as the control ratio departed farther from unity and the modified signals would approach rectangular wave shapes at the limiting control ratios. Unless instantaneous compression is limited to a very small part of the signal range, an incomplete instantaneous expandor (inverse rooter) is required at the distant end which does the reverse of what is done at the transmitting end to restore the signal to substantially its original form. Due to the characteristics of the compressed signals, however, a transmission bandwidth without appreciable amplitude or phase distortion of two to three times the normal is necessary for high quality transmission.

Rectified Control

To avoid the necessity of transmitting such a wide band of frequencies, as well as to permit the use of a single device without restoring, in which case the distortion is limited to a value which is permissible from the standpoint of a listener, practical devices do not operate instantaneously. Instead, the gain is controlled by the charge on a condenser, which is controlled by rectified waves. The action of such an arrangement will now be discussed.

Consider a wave formed by subtracting two sine waves equal in amplitude, one having a frequency 10 per cent less than the other.* A portion of such a wave is shown in Fig. 3*a*. This wave is equivalent to a cosine wave of frequency one-half the sum of the two frequencies, as shown by the instantaneous voltages of Fig. 3*a*, multiplied by a secondary wave (envelope) of frequency one-half the difference of the two original frequencies.

The instantaneous voltages of the wave of Fig. 3*a* vary from a positive maximum through zero to a negative maximum. Curve *a* of Fig. 4 is a summation of most of the instantaneous e.m.f.'s of Fig. 3*a* with respect to their occurrence. About 99 per cent of the instantaneous voltages are in the ranges shown, the remainder being in the range between the upper and lower halves of Fig. 4.

* This illustration is not directly comparable with speech, but it contains some of the attributes which are comparable in this analysis, besides being readily reproducible and relatively simple.

Figure 3*b* indicates values for the same wave in which the negative ordinates have their signs reversed by means of an ideal full-wave rectifier. The resulting wave contains frequencies which were not present in the original, prominent among them being second and higher harmonics of the original. The range of instantaneous values shown

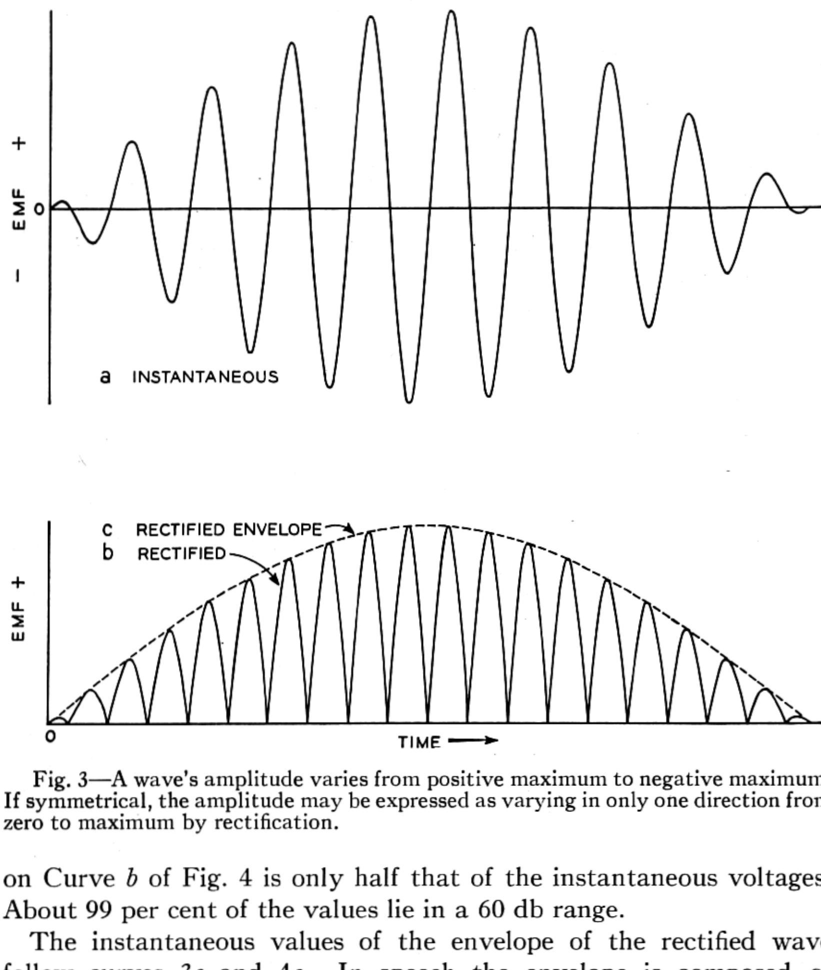

Fig. 3—A wave's amplitude varies from positive maximum to negative maximum. If symmetrical, the amplitude may be expressed as varying in only one direction from zero to maximum by rectification.

on Curve *b* of Fig. 4 is only half that of the instantaneous voltages. About 99 per cent of the values lie in a 60 db range.

The instantaneous values of the envelope of the rectified wave follow curves 3*c* and 4*c*. In speech the envelope is composed of many rather low frequencies which are determined by the rates of enunciation of syllables. For this reason they are sometimes called the syllabic frequencies. If it were possible to make the control vary as a function of the envelope, the result of using a control ratio of 1/2 on the wave of Fig. 3*a* would be as shown in Fig. 5*c*. This was obtained by multiplying the original wave by a factor which is inversely proportional to the rectified envelope. For comparison, the original wave is shown in Fig. 5*a*, and the result of instantaneous compression

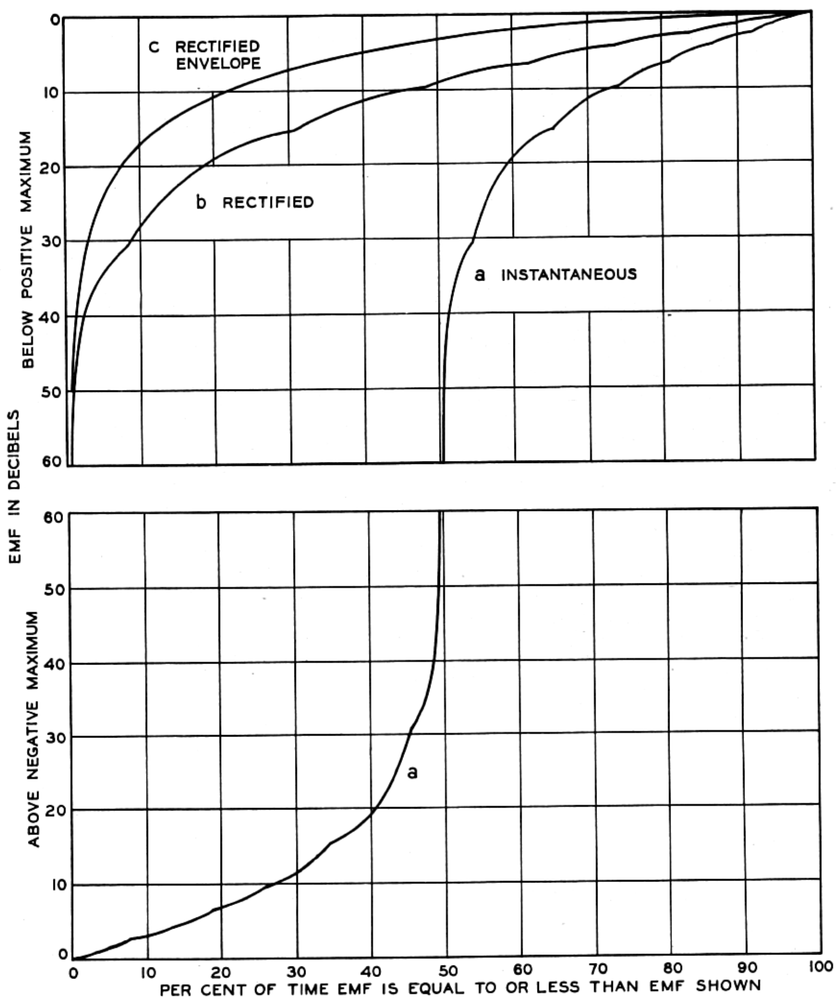

Fig. 4—The amplitude range of the wave of Fig. 3 is infinite on a db scale but most of the values are bunched in a much smaller range.

by the same control ratio in Fig. 5*b*. It is assumed that the arbitrary reference voltage which is not changed by compression corresponds to the maximum value of the input wave, although any other value might be used instead. It is evident from Fig. 5 that envelope com-

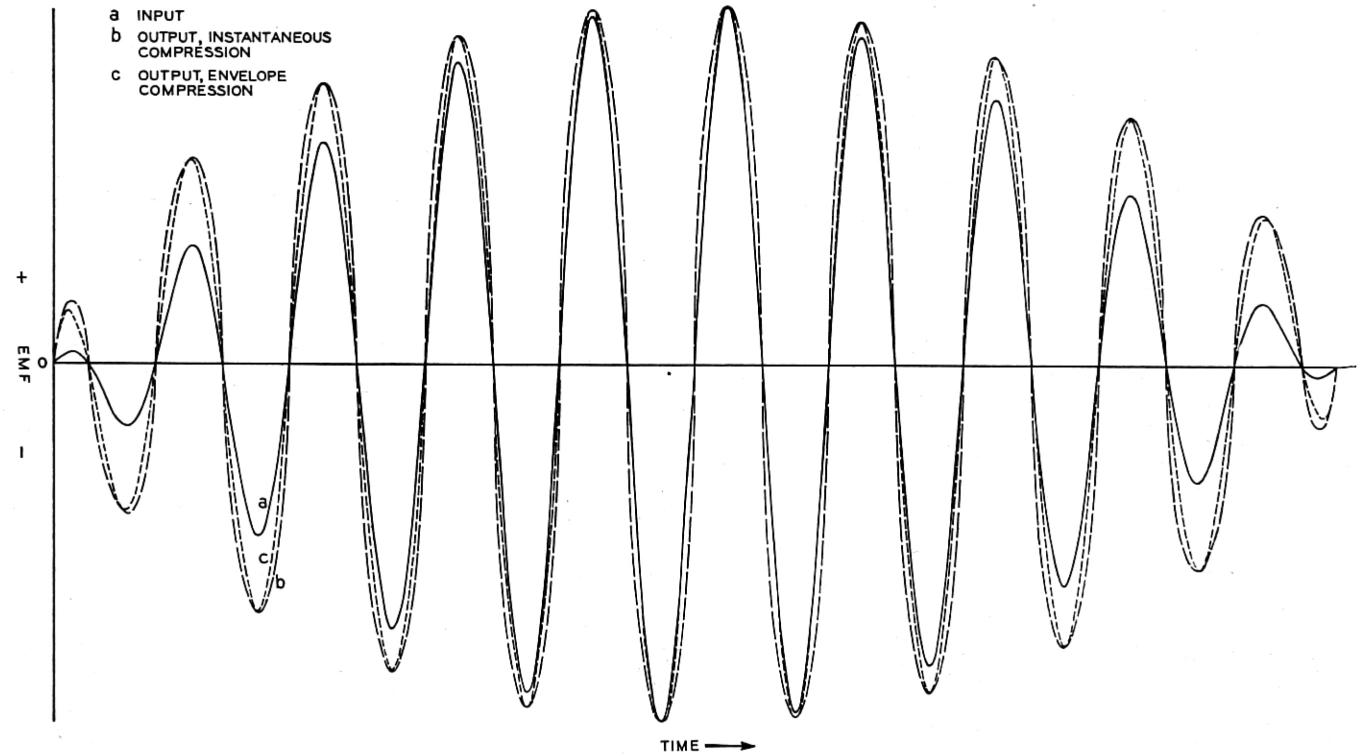

Fig. 5—A wave is compared with two corresponding compressed waves using a control ratio of 1 : 2. For instantaneous action the loops are relatively wider than the original, while in envelope compression the shape is more nearly retained. In both cases the amplitudes of the weak peaks are increased relative to the strong ones.

pression would result in less distortion than instantaneous compression. The extra frequencies formed that were not present in the original wave are the envelope frequencies, so that the additional band required to transmit this wave faithfully is negligible.

Dynamic Operation

The measurements [2] and adjustments of speech amplitudes in common use are made with devices that integrate the effects of the wave over certain time intervals. They do this in a rather complicated manner, however, so that it is difficult to express the resulting quantities in terms that are generally understood.

In the measuring instruments the rectified voltages are impressed on a condenser before being sent through a meter. The readings of the meter are, therefore, proportional to the voltage on the condenser modified by the damping of the meter. The voltage is made up of the sum of the effects of all the instantaneous voltages that have been applied to the condenser from the beginning of time to the instant under consideration. These effects die out so rapidly, however, that the instantaneous voltage on the condenser is practically determined by the voltages received in the immediate past. The condenser may be said to have a memory but a short one. In range control devices, the condenser forms the voltage which determines the amplification of the device.

To distinguish this voltage on the condenser from the applied voltage at any instant, we may call the former an "impression" of the original wave. If the time constant RC is small we get strong impressions similar to the rectified applied wave and its envelope, and if it is large we get weak impressions quite different from the applied wave but something like the rectified envelope.

Figure 6 shows the impressions of the wave of Fig. 3*a*, using four different values of time constant RC as compared to P, the period * of the envelope. Figure 7 shows smoothed summation curves of the impressions of Fig. 6 formed during the time $P/2$. Comparing this with Fig. 4, it is evident that the "bunching" effect for the distribution of impressions is largely between those for the rectified instantaneous and envelope curves. For the longer time constants, i.e., weak impressions, this is not the case for the weaker e.m.f.'s.

* This is twice the duration of Fig. 3, since only half a cycle is illustrated. It is assumed that C is completely discharged at the time this wave is applied. In practice, the rectifier impedance varies with the applied e.m.f. so that the results are not as simple as in this illustration. In general, the time actions are different depending on whether the applied e.m.f. is increasing or decreasing.

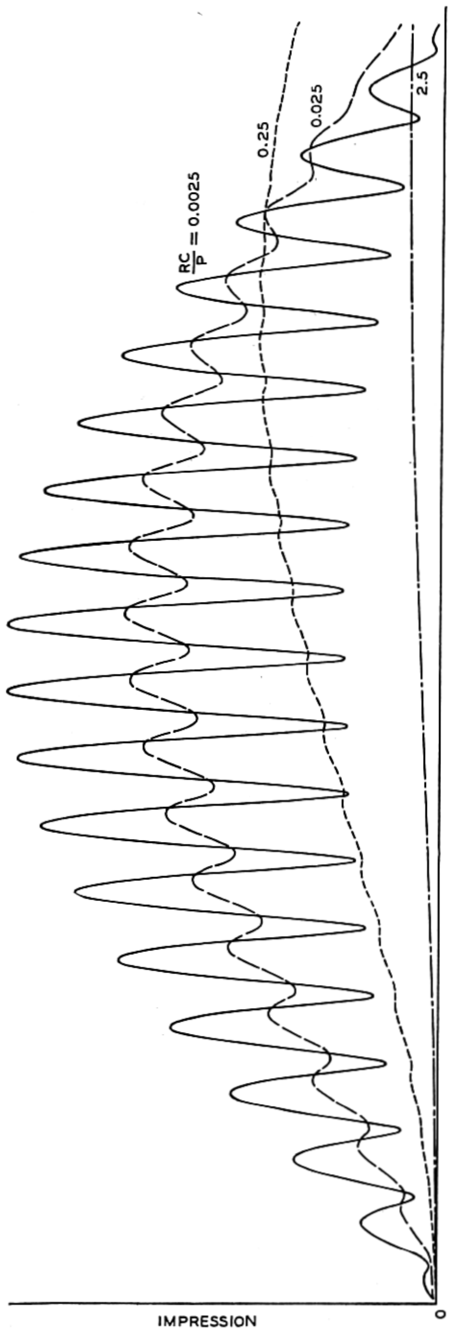

Fig. 6—An integration of Fig. 3*b* differs from the original wave and lags behind it by increasing amounts as the time constant is increased.

Referring again to Fig. 6, it will be seen that for the two smaller values of RC/P the impression curves are composed of (1) the envelope frequency, (2) double the fundamental frequency, and (3) a small delay which can often be neglected. An approximation to envelope compression is therefore possible by choosing RC/P to be in the proper range, i.e., .0025 to .025, and making the output vary as a root or power of the impressions thus formed.

Figure 8 shows the result of compressing the wave of Fig. 3*a* by using the impressions of Fig. 6 to determine the amplification. It was

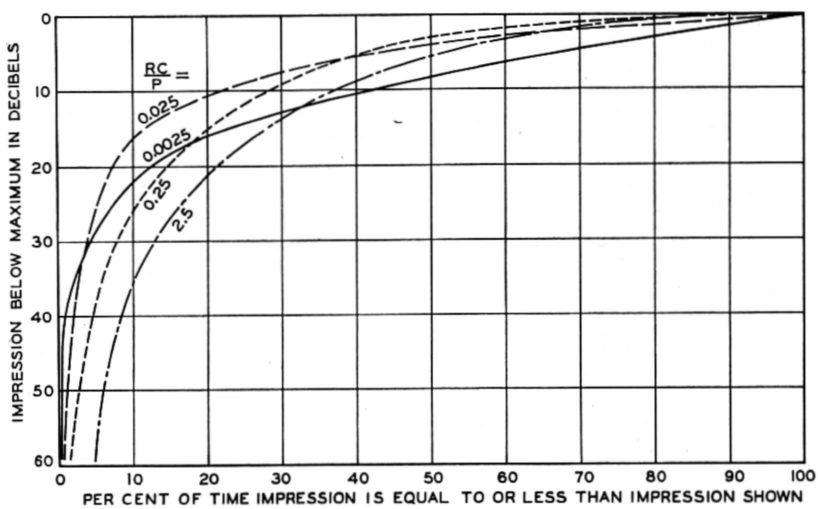

Fig. 7—The amplitude ranges of the impressions shown in Fig. 6 are bunched differently, depending on the time constant. A "volume" measurement means that a given impression is exceeded a small percentage of the time. In speech the peaks are relatively higher than in the wave illustrated.

assumed that the amplification varies in inverse proportion to the square root of the impression. The resulting waves for $RC/P = .0025$ and .025 (medium impressions) are recognizable as something like the original wave. However, for the larger values of RC/P (weak impressions), the distortion at the beginning of the wave is quite large. This is because the impressions are formed so slowly that a longer time is required to drive the gain down to the desired value.

In order to compare impression compression with instantaneous compression, the ordinates of Fig. 5 and 8 were plotted in Fig. 9. This shows that the greatest possibilities of bunching the waves into a narrow range result from the use of instantaneous compression (*b*), since the ratio between any value and the maximum is modified by the

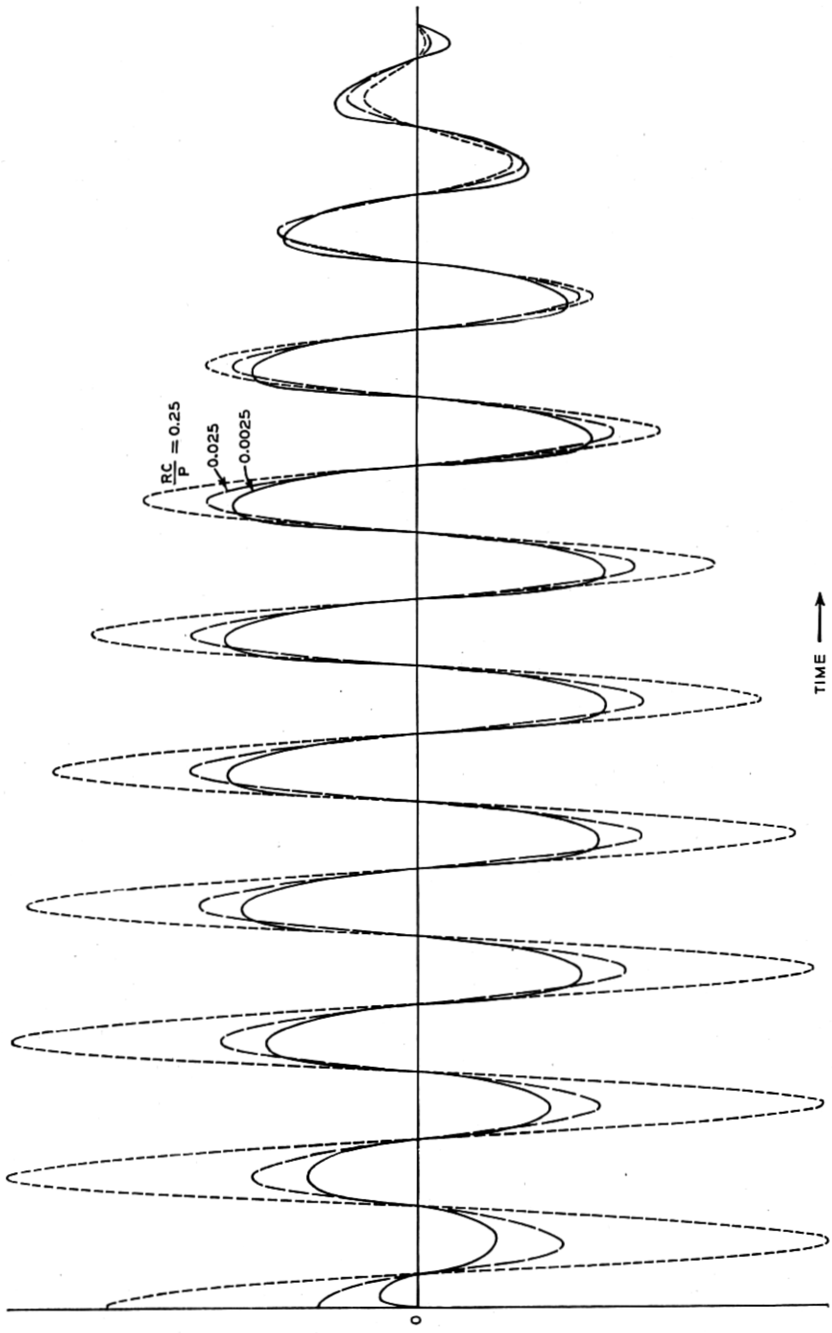

Fig. 8—The wave of Fig. 3*a* is shown here as compressed (1 : 2) by gain changes determined by the impressions of Fig. 6. The smallest time constant gives a result approaching instantaneous compression as in Fig. 5*b*. The next size approaches envelope compression as in Fig. 5*c*. The largest size shown results in considerable distortion, particularly at the beginning. The distortion of the fourth is too large to be shown on the same scale.

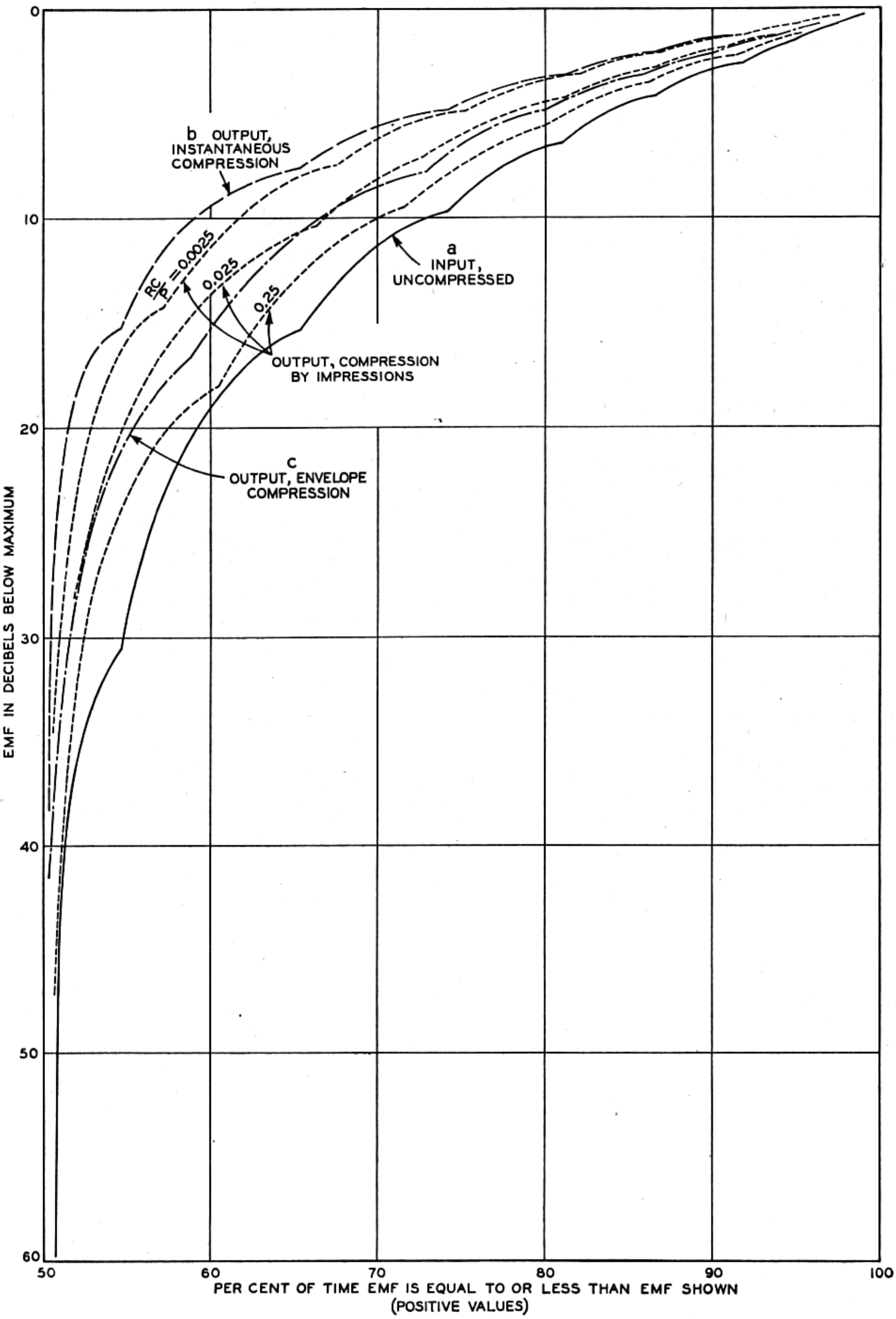

Fig. 9—The amplitude ranges of the compressed waves of Fig. 8 are shown, together with those of Fig. 5. The amount of signal modification (and noise improvement) for any amplitude below maximum may be correlated readily with the time constant.

control ratio. In the case of envelope compression (*c*), the lag causes a reduction in the amount of compression of the instantaneous voltages and the result is seen to be about half way between curves *a* and *b* of Fig. 9. The remaining curves of Fig. 9 are representative of the device [3] used on the long-wave transatlantic radiotelephone circuit.

Volume Control

To avoid both a large range and also the necessity for a continuous record, practical speech amplitude measuring instruments are not directly concerned with either instantaneous, envelope, or impression voltages. Instead a value is determined, corresponding to an impression which is exceeded only a small percentage of the time. This is the principle underlying speech measurements with "volume indicator" type of instruments. In the case of speech, which is much more complex than the simple wave we have discussed, curves like Fig. 9 are steeper, i.e., there are relatively more peaks and a larger range to complicate the problem.

A particular device capable of compressing according to the requirement that the dynamic "volume" range should be reduced, is attained by a combination of several separate range controllers. One is provided to reduce the gain very rapidly when the output volume is too high. A second increases the gain, at a much slower rate, when the impressions formed on the condenser are consistently too low. A third disconnects the condenser from the input when the applied voltage is very small, so that the distortions inherent in change of gain by weak impressions will occur only at times of large and sudden decreases of volume. In the device [4] employed to control volumes applied to a radio transmitter at Norfolk, Virginia, a fourth control provides for rapid partial compression of high peaks, thus improving the modulation. It is unnecessary to re-expand for the purpose of restoring the intelligibility, since the distortion is virtually limited to a change in loudness.

Part 3—Range

Range controllers, like repeaters and attenuators, are limited as to the input range they can accept and the output range they can provide. These limits may be due to thermal noise at the low end and output carrying capacity at the high end. Heretofore, in this paper, the terms "input" and "output" have been purposely left somewhat vague so as to be as general as possible. However, the limits of input and output of a range controller take on particular significance when it is considered that the signal input range may differ both from the input range of the device, and also from the range over which control is exercised.

This control range may be defined as the difference between the maximum and minimum values of an applied wave over which a device is designed to function in a specific non-linear manner. It is usually expressed in db, and may apply to any measure of the applied signal, such as instantaneous voltage, rms steady-state sine waves, or a dynamic measure such as volume. The values dividing the controlled range from the uncontrolled ranges may be referred to as the "control points."

Certain advantages in some cases have been found from restricting the control range. This is accomplished by placing one or both of the control points inside the useful amplitude range. The position of the control point may be moved arbitrarily over a wide range by putting an ordinary repeater (or attenuator) in tandem with the range controller. A given amount of compression at the high amplitude end of the range gives a real signal-to-noise advantage for a much greater proportion of applied e.m.f.'s than the same amount of compression at the low end of the range. In either case the distortion would be less than that of a full range compressor. When expandors with limited range are used, they are subject to the limitation that variations in the medium are increased, but to a lesser extent than full range expandors.

Part 4—Classification of Range Controllers—Secondary Characteristics

Table I, page 536, suggests how the conceptions of control ratio, time actions and range already discussed might be employed to distinguish a variety of devices. In cases where more than one device is covered by a given control ratio and time action the distinction is that the ranges are different. The names of devices used in this table are those which have been used in the past to distinguish the devices one from another.

Nomenclature

Using the above conceptions of the three primary characteristics, it has been found possible to devise a notation to distinguish all the known devices in this field. As an example of how this proposed system of nomenclature would be applied, Table II, page 537, gives three columns. Column 1 sets forth the arbitrary names that have been used in the past to distinguish certain devices which have come into use. Column 2 gives descriptive names which specify the three fundamental characteristics. In column 3 each device is named by three symbols defining the three fundamental characteristics, and a

TABLE I

Classification of Range Controllers

Typical Time Actions	Compressors ($r < 1$)		Expandors ($r > 1$)	
	Full Range	Limited Range	Full Range	Limited Range
Instantaneous	Rooter	Peak Chopper, Voltage Limiter	Inverse Rooter, (Squarer)	Voice Operated Relays, Cross-talk Suppressor
Syllabic	Compressor	Limited Range Compressor, Peak Limiter	Expandor	Noise Reducer
Volume	Vogad, Range Reducer	Volume Limiter, Half Vogad	Range Restorer	

classification which tells what the device is designed to do. In this system the numbers preceding the letters specify the input control range in decibels, and the position of a horizontal bar indicates the position of the main signal range with respect to the control range.

The letters specify the time actions and in the case of vogads, where several time actions may be combined, an arbitrary combination of letters would be used. The final numbers specify the control ratio, and in the case of vogads, where this might be different depending on whether the input was increasing or decreasing, both values are given, the former first.

In this system, definitions of time actions are prerequisite and by way of illustration, the following symbols have been used:

I represents instantaneous, meaning very fast adjustment of device

S represents syllabic, meaning moderate speed adjustment of device

V represents volume, meaning a combination of controllers which produces adjustment of device in response to dynamic speech so that the output volume is approximately determined by the input volume.

Secondary Characteristics

In addition to their three primary characteristics, range controllers may have a number of secondary features which are sometimes important. The outstanding ones are:

1. Bias

A *neutral* range controller is one which holds its setting during the quiet periods between words and sentences and which changes its gain

TABLE II

COMPARISON OF NOMENCLATURE FOR RANGE CONTROLLERS

Col. (1) Arbitrary [1]	Col. (2) Systematic	Col. (3) Symbolic
1. Vogad	Full Range 45 db Volume Compressor	45 *VSI* 23–18 Compressor
2. Vogad Combined with Syllabic Compressor	Full Range 45 db Volume Compressor	45 *VSSI* 23–18 Compressor
3. Volume Limiter	High Range 15 db 1 : 5 Volume Compressor	$\underline{15}V5$ Compressor
4. Compandor	Full Range 60 db 2 : 1 Syllabic Compandor	$60S2$ Compandor
5. Noise Reducer	Low Range 20 db 2 : 1 Syllabic Expandor	$\overline{20}S2$ Expandor
6. Limited Range Compressor	High Range 10 db 1 : 2 Instantaneous Compressor	$\underline{10}I2$ Compressor
7. Peak Limiter	High Range 12 db 1 : 5 Syllabic Compressor	$\underline{12}S5$ Compressor
8. Peak Chopper	High Range 6 db 1 : 100 Instantaneous Compressor	$\underline{6}I100$ Compressor
9. Crosstalk Suppressor	Low Range 10 db 10 : 1 Instantaneous Expandor	$\overline{10}I10$ Expandor
10. Rooter and Inverse Rooter	Full Range 70 db 2 : 1 Instantaneous Compandor	$70I2$ Compandor
11. Vodas (Singing Suppressor Relay)		$0I\infty$ Expandor
12. Syllabic Vodas		$0S\infty$ Expandor

only when the waves acting on it differ from those just received. This condition sets a new requirement on the range controller which can usually be met by a combination of control circuits.

A *biased* controller is one which returns to a setting corresponding to some fixed or biased intensity when speech is not passing and adjusts itself each time speech begins. A simple compressor is biased since with no input it generally takes a setting of maximum gain so as to be right for the weakest waves that might be applied in its working range or below the working range. It is also possible to bias a range controller so as to have minimum gain, or any other intermediate value when no waves are applied. An important secondary characteristic is the rate at which the device returns to the desired "bias" point.

Any of the devices listed in the tables might be neutral or biased in either direction, thus increasing the number of possible arrangements.

2. *Behavior Outside of Range*

For inputs outside the working range of a range controller it is important to provide that the amplification of these waves does not cause them to be modified so as to be out of proportion to output signals in the main range. In some cases this is met by choosing a device which follows the same law all the way to zero current. In others, the device may act as a linear transducer, i.e., with range factor of one outside the working range. Various other combinations of control ratios can, of course, be employed.

3. Pilot Channel

In all complete compressors some form of pilot channel is necessary to control the re-expansion if this is required. If the gain changes are slow, the pilot channel may include an operator who changes the gain of the receiving device in a manner complementary to that of the sending device based on aural or visual signals. If the gain changes are too rapid for the operator to follow, the receiving gain may be changed automatically.

The pilot channel itself may be a direct or alternating current of variable amplitude or frequency, or in case of carrier or radio, it may be the carrier frequency. In sound reproduction a pilot channel might be a pilot track on the record.

Summary

In an amplitude range control system, the following characteristics must be specified in addition to the usual repeater characteristics, to determine its design and performance:

1. The steady-state control ratio, which determines how much control is obtained and whether restoration can be made automatically or not.
2. The manner in which the output varies with time, following a given change in input.
3. The range over which it is to function.

In specific cases the following should also be considered:

4. The action of the device for inputs outside the working range.
5. If the device is a complete compressor, the type of pilot channel for restoring.
6. The action of the device when signals are removed.

Acknowledgment

The computations used to obtain Figs. 3 to 9, inclusive, were made by Miss Marian Darville.

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