ARTIFICIAL RECONSTRUCTION OF SPEECH

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FIG. 1

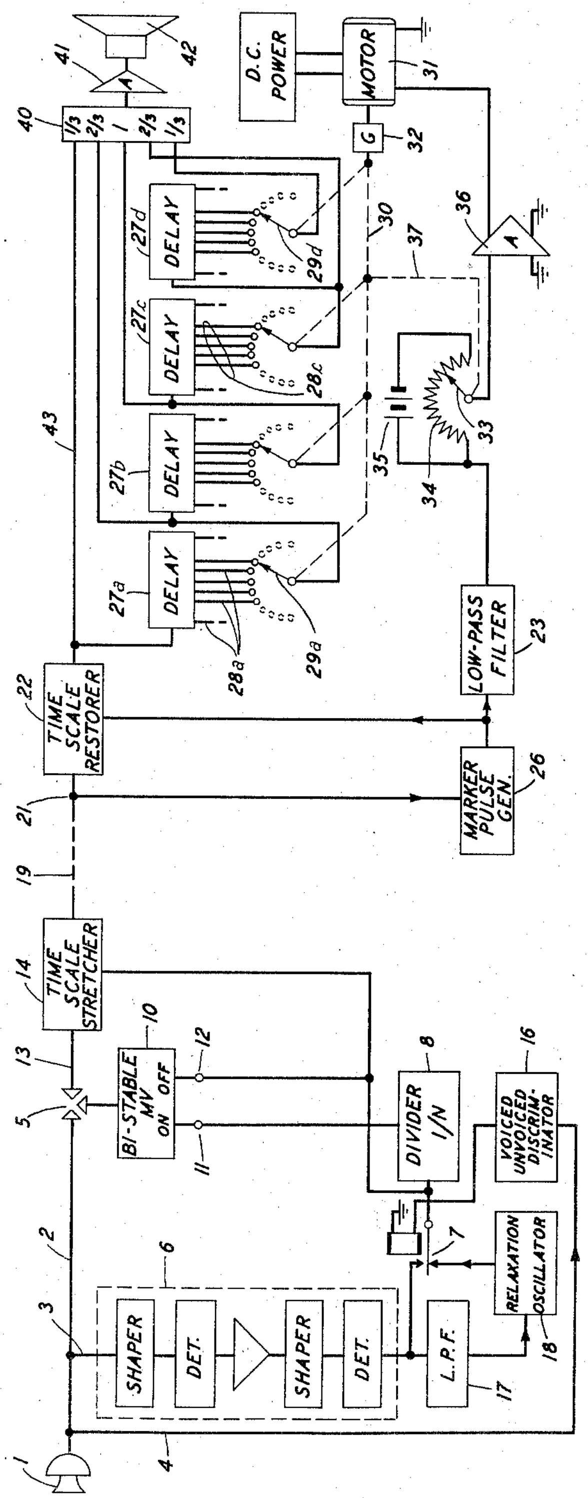



FIG. 9

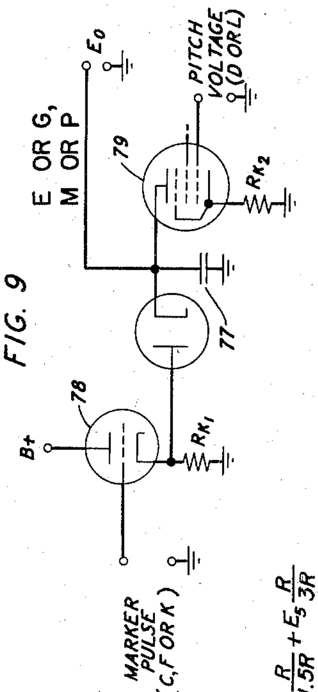
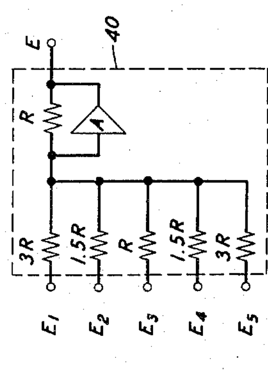



FIG. 2



$$E = E_1 \frac{R}{3R} + E_2 \frac{R}{1.5R} + E_3 \frac{R}{R} + E_4 \frac{R}{1.5R} + E_5 \frac{R}{3R}$$

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FIG. 3

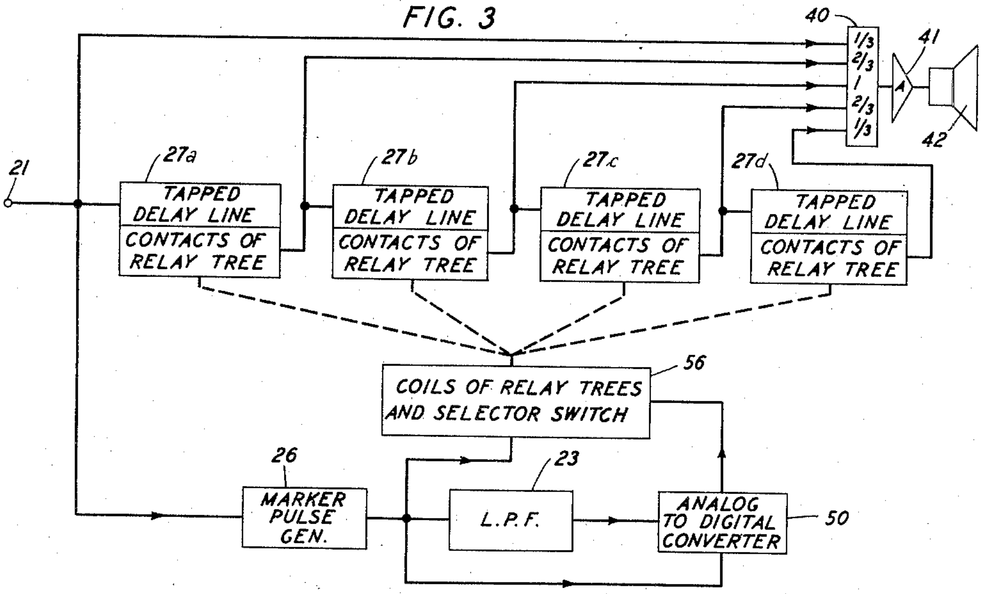


FIG. 4

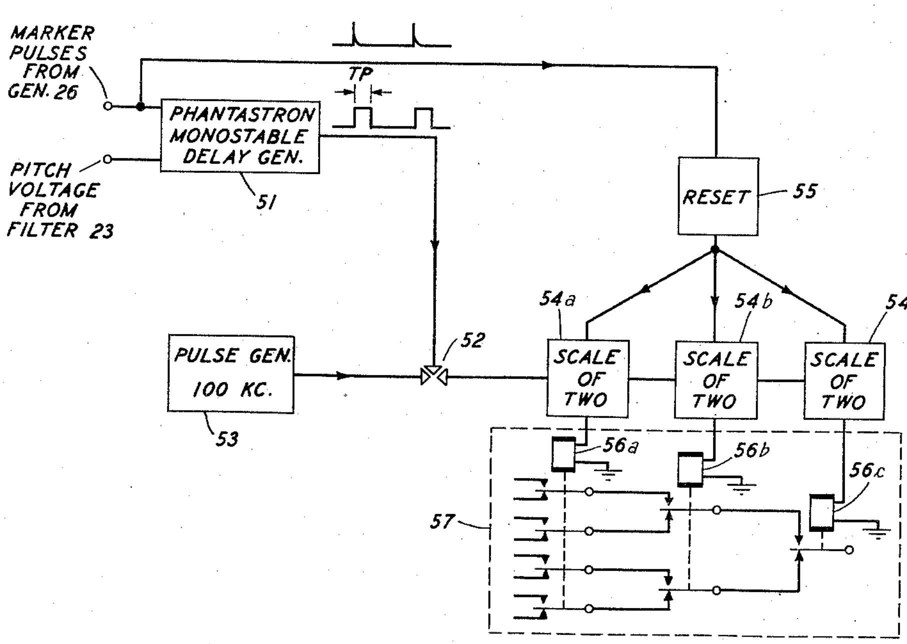


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FIG. 5

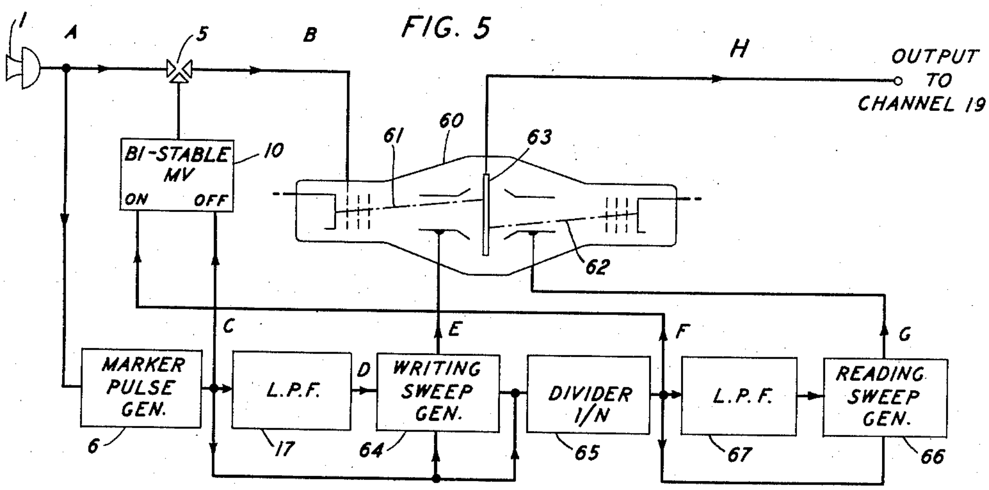


FIG. 6

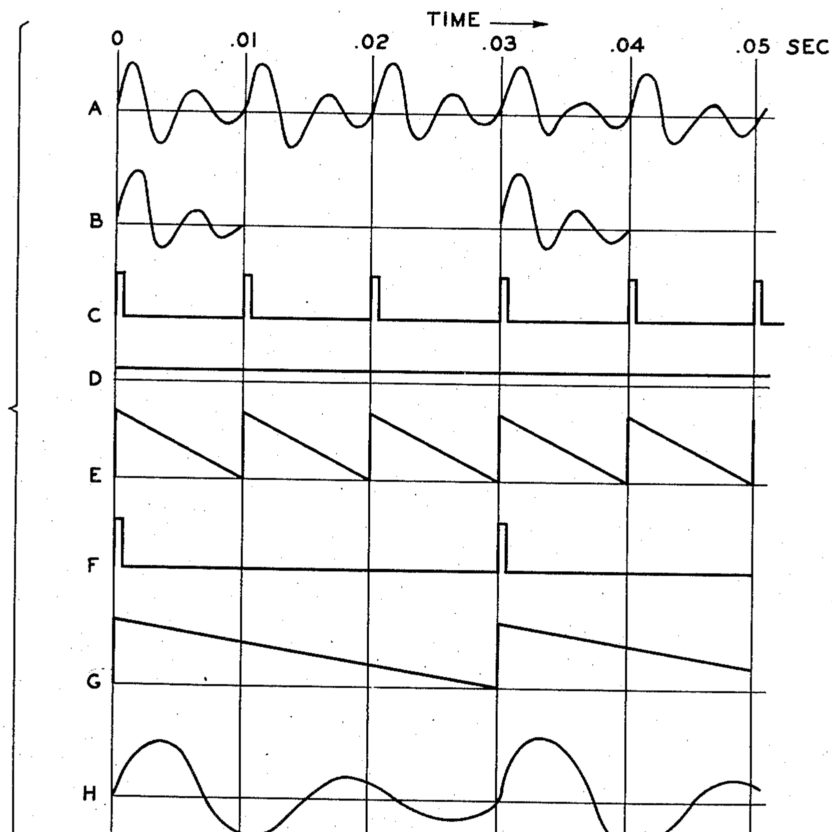


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FIG. 7

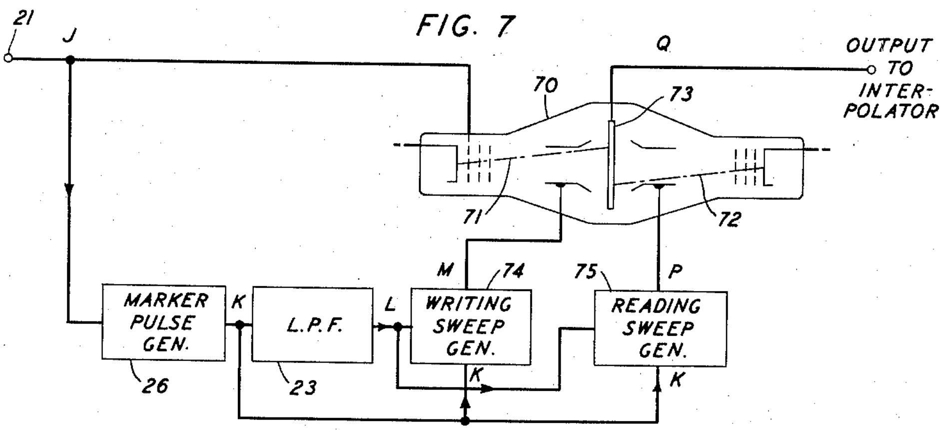


FIG. 8

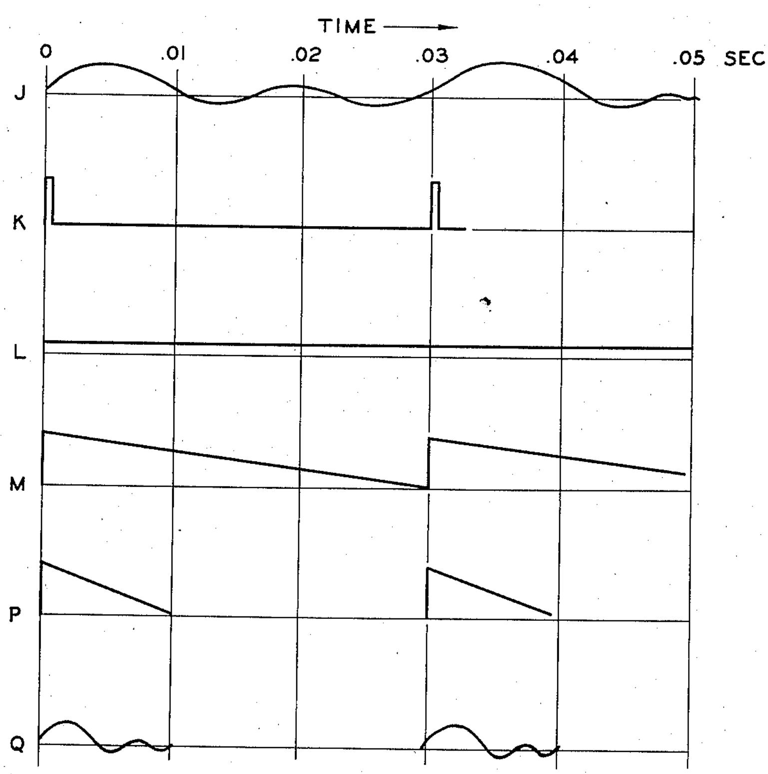


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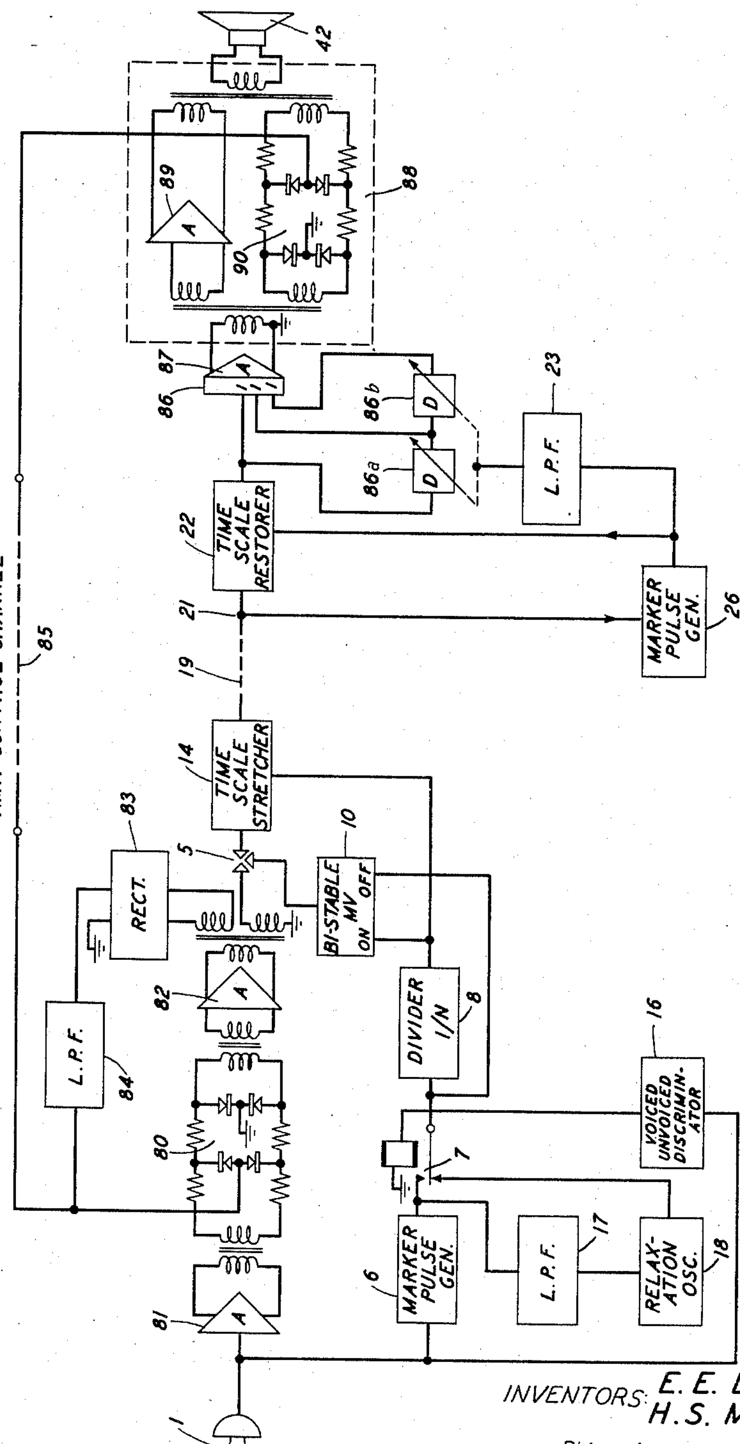
FIG. 10

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2,860,187

# ARTIFICIAL RECONSTRUCTION OF SPEECH

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Application December 8, 1955, Serial No. 551,940

14 Claims. (Cl. 179—15.55)

This invention relates to economy of frequency bandwidth in telephony, and particularly to the artificial reconstruction of speech from narrow band transmitted signals. The principal object of the invention is to improve the quality of such artificial speech.

It has long been known that a speech wave is almost periodic in character, the difference between the wave of each period and the wave of the following period being small compared with the variations of the wave within any period. Many proposals have undertaken to turn this situation to account in the reduction of the band of frequencies required for the transmission of the information content of the speech wave. According to one such proposal, described by H. W. Dudley in his Patent 2,115,803, May 3, 1938, an electrical speech wave originating, for example, in a microphone, is chopped in synchronism and in phase with its fundamental period and certain full periods, for example every other one, are discarded. The retained periods are transmitted to a receiver station, preferably after stretching each one in the time dimension to fill the gap left in the wave train by elimination of the discarded period. Such stretching carries with it a corresponding reduction in the frequency band required for transmission. At the receiver station the received wave is restored to its original dimensions in time and frequency, thus leaving blank intervals corresponding to the eliminated periods. The teaching of the Dudley patent is to fill each of these gaps or blank intervals with one or more repetitions of the last received period. As a result the reconstructed wave comprises a sequence of identical periods, followed by another sequence of mutually identical periods, and so on. The price paid for the bandwidth economy in transmission is therefore an increase in the abruptness with which the waveform of each such group of periods changes to that of the next such group. Thus, for example, when two out of each group of three successive periods of a changing speech wave are eliminated at the transmitter, i. e., with a chopping factor $N=3$, the transmission band can in principle be reduced by a factor of three; but the abruptness of transition, at the receiver, from the last of each group of three like periods to the first of the following group of three like periods, is likewise increased by a factor of three.

This abruptness of transition naturally makes for noise and unnaturalness in the reconstructed speech. It is a specific object of the present invention to reduce the noise and distortion which arise in a chopped speech transmission system for these reasons. This object is attained, in accordance with the invention, by inserting in each blank interval of the received wave, not merely a repetition of the last received period, but a modification of it. One such modification is a weighted average of the two waves which respectively precede and follow the blank interval. Thus, if the blank interval is only a single period in length, (i. e., if the chopping factor N has the value 2) the preceding and following waves are weighted alike and the modified wave is obtained by adding them together and dividing by two. If, rather, three periods out of each group of four have been eliminated from transmission ($N=4$) three blank intervals are to be filled in. The first of these is filled with a wave which is a mixture of three parts of the preceding transmitted wave and one part of the following transmitted wave. The second blank interval is filled in with an equal mixture, while the third is filled with a mixture of one part of the preceding wave and three parts of the following wave. The apparatus thus averages the waveforms of earlier and later transmitted waves, and from such averages constructs artificial waves and inserts them in the blank intervals.

One of the principal differences between each period of a speech wave and the next is a difference in amplitude. Indeed, some experimental evidence indicates that this is the most important single difference. Accordingly, the invention also provides a simplified system in which amplitude differences are taken account of in the intercalation of artificial wave periods between successive transmitted wave periods, while disregarding other differences. In this simplified system an auxiliary amplitude control signal is derived at the transmitter station and is transmitted, along with the chopped speech waves, to the receiver station where it controls the amplitudes of repetitions of each transmitted speech wave for insertion in the blank interval which follows it.

To provide that the auxiliary gain control signals shall affect only the repetitions of the received wave and not the received period on its first occurrence requires switching apparatus of some complexity, operating in synchronism with the fundamental pitch frequency or a subharmonic thereof. In accordance with a further feature of the invention these complications are avoided by use of compandor apparatus including an amplitude compressor at the transmitter station and a corresponding amplitude expandor at the receiver station. The amplitude control signal, which modifies the amplitudes of the repetitions of the received wave at the receiver station, may conveniently be derived from the compressor at the transmitter station. With this arrangement the amplitude control signal may be applied to the final output signal at the receiver station including each originally received period as well as its various repetitions.

The invention will be fully apprehended from the following detailed description of preferred embodiments thereof taken in connection with the appended drawings in which:

Fig. 1 is a block schematic diagram showing a transmission system embodying the invention;

Fig. 2 is a schematic circuit diagram showing a weighting network for use in the apparatus of Fig. 1;

Figs. 3 and 4 are block schematic diagrams showing electronic alternatives to the interpolator of Fig. 1;

Fig. 5 is a block schematic diagram showing an electronic version of the time scale stretcher of Fig. 1;

Fig. 6 is a group of waveform diagrams of assistance in explaining the operation of Fig. 5;

Fig. 7 is a block schematic diagram showing an electronic alternative to the time scale restorer of Fig. 1;

Fig. 8 is a group of waveform diagrams of assistance in explaining the operation of the apparatus of Fig. 7;

Fig. 9 is a schematic circuit diagram showing structural details of a part of the apparatus of Fig. 7; and

Fig. 10 is a block schematic diagram of apparatus embodying the invention in a modified form.

Referring now to Fig. 1, a speech signal which may be derived from a source such as a microphone **1** is passed into a transmission path **2** and two control paths **3**, **4**. The transmission path **2** includes the two conduction terminals of a switch or gate **5** to whose control terminal a control signal derived in the first control path 3 is applied.

The first control path 3 comprises a period marker pulse generator which may advantageously be of the type which forms the subject matter of E. Peterson Patent 2,593,694, issued April 22, 1952, and which is further described by O. O. Gruenz, Jr. and L. O. Schott in an article published in the Journal of Acoustical Society of America for September 1949 (volume 29) page 487. The principal feature of this generator is a detector followed in tandem by a shapnig network which accentuates the amplitudes of low frequency components at the expense of higher harmonic component amplitudes. Preferably, each of these steps is carried out two or more times in succession, and all of them may be preceded by an auxiliary shaping step as by the first unit shown. With this arrangement, as is more fully described in the patent and publication referred to above, the output of the generator 6 comprises a single sharp spike of current which occurs at the instant of each major peak of the speech signal wave, or between the principal zero and the major peak. For present purposes, the principal zero is the last zero value or axial crossing of the speech wave preceding each of its major peaks.

When the speech is "voiced," its waveform is periodic, and this marker pulse thus indicates the instant of inception of each full period of the speech wave, and the frequency at which such pulses are repeated is the fundamental pitch frequency of the speech wave.

For voiced sounds of speech, the train of marker pulses is applied through the front fixed contacts of a relay 7 to a frequency divider 8, for example a multivibrator, proportioned to deliver one output pulse for every N input pulse. The input terminal of the divider 8, bearing a train of marker pulses which recur at the recurrence rate of the major peaks of the speech wave, is connected to one input terminal 12 of a bistable multivibrator 10 while the output terminal of the divider 8, bearing a train of pulses whose repetition rate is $1/N$ times the fundamental frequency of the speech wave, is applied to a second input terminal 11 of the bistable multivibrator 10. This multivibrator 10 and the arrangement of its input terminals and its output terminals with respect to its internal structure are such that application of a pulse to its inpult terminal 11 produces a signal on this output terminals, while application of a pulse to its input terminal 12 terminates this signal. As a result, the output signal of the bistable multivibrator 10 operates to close the switch 5 at the inception of a period of the speech wave while cessation of this output signal, which takes place at the conclusion of this speech wave period, opens the switch 5 and so prevents conduction of the ensuing speech wave periods until the next output pulse of the divider 8 appears. Thus, of every N successive period of the speech wave, $N-1$ of them are blocked.

The switch 5 thus operates to chop any voiced speech wave synchronously with its successive fundamental periods, passing one out of every N such period and leaving blank intervals in the signal on the conductor 13 corresponding to the remaining $N-1$ of such periods. The signal as thus chopped may be transmitted to a receiver station without further change. It is advantageous, however, to turn the blank intervals thus produced to account, either by reducing its vulnerability to noise, by reducing the bandwidth required to transmit it, or in some other fashion. By way of example a time scale stretcher 14 is included in tandem with the outgoing conductor 13. Its construction may be of any desired sort, for example as described in the aforementioned patent of H. W. Dudley. It is controlled in its stretching action by the output of the marker pulse generator 6. If preferred, various electronic counterparts may be employed instead of Dudley's apparatus. Whatever the structural details of the time scale stretcher 14 may be, its operation is to stretch each full period which passes through the gate 5 over the ensuing $N-1$ blank intervals.



The second control path 4 extends from the output terminal of the microphone 1 to a discriminator 16 as between voiced sounds and unvoiced sounds. This unit is well known and may have any desired construction. For example, it may comprise a band-pass filter, a rectifier and a low-pass filter connected in tandem in the order named. The band-pass filter being proportioned to pass only the principal frequency components of voiced sounds, e. g., those in the range 60–1,000 cycles per second, and the low-pass filter being proportioned to pass only frequencies of syllabic rates, e. g., those in the range 0–25 cycles per second, the unit gives an output signal of substantial magnitude when the sound waves impinging on the microphone 1 are of the voiced variety, and gives no such output signal when the sound is unvoiced.

The output signal of this discriminator 16 is applied to the winding of the relay 7 and serves to actuate it and to hold its moving contact against its front fixed contacts when the sound is voiced. This permits the output pulses of the marker pulse generator 6 to follow the path hereinabove described. When, to the contrary, the sound is unvoiced the moving contact of the relay 7 falls against the back fixed contact. In this condition of the relay 7 the output pulse train of the marker pulse generator is converted to a slowly varying signal by a low-pass filter 17 and this signal is applied to a relaxation oscillator 18 which delivers pulses at a slowly varying but nearly regular rate through the back fixed contact to the moving contact of the relay 7. The output pulses of the relaxation oscillator 18 thereupon follow the paths hereinabove described for the output pulses of the marker pulse generator 6.

The marker pulse generator 6 delivers a pulse for every major peak of the speech wave. When the speech wave is of the voiced character these marker pulses recur periodically at the fundamental pitch rate. When, to the contrary, the sound is unvoiced, the marker pulses recur at randomly spaced instants on the time scale, and at an average rate lying within the normal pitch range. For effective chopping of the wave of an unvoiced sound the chopping should occur in a regular fashion. It is the function of the combination of the relaxation oscillator 18 and the low-pass filter 17 to substitute, at the control terminals of the gate 5 and of the time scale stretcher, 14, a comparatively regular train of pulses which recur at the average recurrence rate of the randomly distributed pulses of the marker pulse train itself.

If preferred, the apparatus shown may be modified in such a fashion that the relaxation oscillator 18 delivers a train of pulses which recur, not at the average repetition rate of the marker pulses during an unvoiced sound, but rather at a rate corresponding to the fundamental frequency of the most recent voiced sound; i. e., at the rate which obtained at the instant of the change of the relay 7 from its voiced position to its unvoiced position. Apparatus of this character is disclosed in an application of H. L. Barney, Serial No. 459,333, filed September 29, 1954, now matured into Patent 2,819,341, granted January 7, 1958.

The resulting signal, stretched in time or otherwise modified as desired, may now be transmitted to a receiver station over a channel 19 which is of much lower quality than would be required for transmission of the unmodified speech wave. Thus, if stretching in time be employed, the bandwidth of the channel 19 is reduced by a factor N as compared with the bandwidth of a channel required to transmit the original speech wave.

Upon arrival at the input terminal 21 the receiver station the received signal is first restored to its original dimensions in the time scale as by a restorer 22 which again may be as described in the aforementioned Dudley patent or an electronic counterpart or refinement thereof.

Inasmuch as any such apparatus must operate in synchronism with the received wave, a period marker pulse generator **26** is shown connected to the input terminal **21** and delivering its output period marker pulses to the control terminal of the restorer **22**. Its construction may be identical with that of the period marker pulse generator **6** at the transmitter station. In addition, the train of period marker pulses, one of which occurs for each period acually received, is converted into a slowly varying voltage as by a low-pass filter **23**. As in the case of the transmitter, these marker pulses are always of the same polarity so that no rectifier is required, and the low-pass filter **23** operates to convert the pulse train into a voltage of varying magnitude proportional to the fundamental pitch of the received signal and of unvarying polarity.

After completion of the time scale restoration, the signal is applied to an interpolator which may comprise a plurality of delay devices **27** connected in tandem. The first of these delay devices **27***a* is provided with a number of lateral taps **28***a*, any one of which may be engaged by a conductive wiper arm **29***a*, and the other delay devices **27***b*, **27***c*, **27***d* are similar in every respect. The several wiper arms **29** are mounted on a common shaft **30** arranged to be driven by a direct-current motor **31**, preferably through a reduction gear box **32**. The full length of each delay device **27** is such that the propagation time of a wave through it from its input terminal to its most distant tap is equal to the longest fundamenal period to be expected; i. e., to the reciprocal of the pitch of the deepest bass voice.

As the speech directed into the microphone **1** progresses, its fundamental frequency changes and the output voltage from the low-pass filter **23** changes proportionally. This voltage is added to a fraction, determined by the position of a wiper arm **33** of the voltage which appears across a resistor **34** which shunts a battery **35**. The sum of these voltages is converted by an amplifier **36** to a driving current for the motor **31**, which drives the wiper arm **33** through shaft **37**. In accordance with the well known behavior of servo systems, the motor **31** then rotates, driving the shaft **37** and the wiper arm **33** in a direction and through an angle such as to bring the net voltage input to the amplifier **36** to the value zero. In doing so, it drives each of the several wiper arms **29** to similarly numbered taps on the several delay lines **27**, and the tap at which each wiper arm comes to rest is that at which the propagation time from the input terminal of any delay line to that tap is equal to the instantaneous value of the fundamental period of the speech wave.

As remarked above the output signal of the low-pass filter **23** is proportional to pitch in contrast to period. Hence the wiper arms **29** of the delay devices **27** are located, in response to the movement of the shaft of the motor **31**, at positions proportional to pitch. Because each wiper arm is required to engage a particular tap of its delay line in a fashion to match individual periods of the wave, an inversion operaton must somehow be effected as between the controlling signal and resulting tap locations along the delay line. This is conveniently achieved simply by numbering the several taps of each delay line starting with the tail end of that line, instead of with its input end, and by an appropriate nonuniform spacing among the taps in accordance with the required reciprocal relation.

The input terminal of the first delay device **27***a* is connected to one input terminal of a weighting network **40** and each of the several wiper arms **29** is connected to another such input terminal. In the example shown in which the value of the chopping factor N is 3, four delay lines **27** are employed and the weighting network **40** has five input points. More generally, for any value of the chopping factor N the number of delay lines **27** required is $2N-2$ and the number of input points to the weighting network **40** is $2N-1$. Again in the example shown the weighting factors of the several input points to the weighting network are, from top to bottom of the figure, ⅓, ⅔, 1, ⅔ and ⅓, respectively. More generally, if the first of two transmitted periods be designated $P_1$ and the next one $P_2$, and if the blank intervals between them to be filled by first order interpolation be designated $P_a$, $P_b$, $P_c$ . . . and so forth the relations which hold between the weighting factors of the several input points of the weighting network **40** are given by the coefficients in the following array:



$$\left.\begin{aligned} P_a &= \frac{N-1}{N}P_1 + \frac{1}{N}P_2 \\ P_b &= \frac{N-2}{N}P_1 + \frac{2}{N}P_2 \\ P_c &= \frac{N-3}{N}P_1 + \frac{3}{N}P_2 \\ . &= \quad . \quad . \quad . \quad . \quad . \\ . &= \quad . \quad . \quad . \quad . \quad . \\ P_{N-1} &= \frac{1}{N}P_1 + \frac{N-1}{N}P_2 \end{aligned}\right\} \quad (1)$$

A weighting network **40** of any desired sort may be employed, a convenient one being shown in Fig. 2 for the illustrative case in which $N=3$. It operates in a manner well known in the art to give the proper weights to the signals applied to its various input points and then to add these weighted signals together in the fashion shown in the figure.

The output of this network **40** thus constitutes a correctly weighted sum of the various inputs. It is applied through an amplifier **41** to a reproducer **42** which delivers acoustic waves of artificial speech.

For a full understanding of the operation of the network **40**, consider an instant at which one of the received wave periods of the speech has passed through the first and the second delay devices **27***a*, **27***b* and has reached the third input terminal of the weighting network **40**. It is then reproduced without change, inasmuch as the weighting coefficient for this input point is unity. One fundamental period later the same wave has passed through the third delay device **27***c* and appears at the fourth input terminal of the weighting network **40**. There it is multiplied by the factor ⅔. At the same instant the next transmitted wave period arrives at the input point to the first delay device **27***a* and is supplied by way of a conductor **43** to the first input point of the weighting network **40** where it is multiplied by a factor ⅓. Hence, the reproduced wave is a mixture of ⅔ of the earlier wave and ⅓ of the later one. It is reproduced as audible sound by the reproducer **42** in the first blank interval following the earlier transmitted wave. Still later by one fundamental period of the speech wave, the earlier transmitted wave has passed through the fourth delay device **27***d* and it is applied to the fifth input point of the weighting network **40** where it is multiplied by a factor ⅓. At the same instant the following transmitted wave has passed through the first delay device **27***a* and has arrived at the second input point of the weighting network **40** where it is multiplied by the factor ⅔. Thus, the reproduced wave is a mixture of ⅓ of the earlier transmitted wave and ⅔ of the later one, and it occurs at a time such that it is inserted in the second blank interval. The next event which occurs is that the following transmitted wave has passed through the first two delay devices **27***a*, **27***b*, and is applied to the third input point of the weighting network **40**. From here on the cycle of operations is repeated.

While the apparatus of Fig. 1 illustrates the principles of the invention the shafts **30**, **37**, the mechanical wipers **29**, **33**, the follow-up motor **31** and associated apparatus impose limitations on the speed with which it can operate. For these reasons an electronic counterpart of the apparatus of Fig. 1 may well be preferred. Such electronic apparatus, an example of which is shown in Figs. 3 and 4, is the same as the apparatus of Fig. 1, except for the substitution of a relay tree and its contacts for the wipers of Fig. 1 and circuits to control the windings of the relay tree for the servo system of Fig. 1. In order always to select a tap that will match the period of the delay lines **27** with the pitch period, the pitch voltage is converted to a number representing the particular tap on each of the several delay lines which introduces a delay approximately equal to the pitch period. To this end the pitch voltage, derived by the filter **23** from the train of marker pulses from the generator **26**, is applied to a converter **50**, whose details are shown in Fig. 4. The pitch voltage is sampled at the instant of a period marker pulse and applied as the initial charge across a Miller type capacitor in a phantastron delay generator **51**, as described, for example, by Chance, Hughes, et al., in "Waveforms" (Radiation Laboratories Series, volume 19, McGraw-Hill 1949), page 197. The phantastron **51** is of the monostable variety and its action is initiated by each marker pulse. The output derived from the screen grid of the phantastron **51**, is a rectangular pulse starting at the instant of a marker pulse, and having a duration directly proportional to the pitch voltage. The duration of the rectangular pulse developed at the screen may be converted into a binary number by applying the pulse to the control terminal of switch or gate **52** which, when its conduction path is thus established, admits a sequence of very rapid pulses from a generator **53** into a string of scale-of-two counters **54**. In a typical system the pulses are generated at a 100 kilocycle rate, so that the counting process is completed in a small portion of a pitch period. The binary state of the group of scale-of-two counters, returned to zero after the completion of each count by a reset circuit **55** under control of each marker pulse, is now directly proportional to that tap of the delay devices **27** whose numerical designation is most nearly proportional to the fundamental period of the speech wave. The coils **56** of a relay tree **57** are connected to the scale-of-two counters **54** in a fashion such that the presence of a "1" closes the relay contacts and the presence of a "0" leaves them open. Thus the relay tree contacts operate to connect the proper tap of each delay device **27**, as indicated by the counters **54**, to the input terminal of the next delay device **27**. As a refinement, the delay devices **27** may be divided into two groups, and the delays for similarly numbered taps in the two groups may be set at two slightly different times; e. g., at times which differ by one pitch period, to avoid switching when signals are present in the delay devices. A second counter and a delayed marker pulse generator may be employed for this purpose.

Returning to Fig. 1, it was remarked above that the time scale stretcher **14** at the transmitter station and the time scale restorer **22** at the receiver station might take the form shown in the aforementioned H. W. Dudley patent. However, especially for cases in which the chopping factor N has the value 3 or more, an electronic apparatus for carrying out these operations may be preferred. Fig. 5 shows one such electronic stretcher which employs a double beam storage tube **60**, for example a tube of the type dsecribed in the "RCA Review" for March 1949 (volume 10) page 59 and is common known as a "Graphechon." This tube generates separate writing and reading electron beams **61**, **62** so that one pitch period of the speech signal can be written on the mosaic of its target anode **63** by the writing beam **61** and the reading beam **62** can scan the target **63** independently. Fig. 5 also shows, in block diagram form, apparatus which acts to chop out an integral number of pitch periods from the speech wave and stretch each retained period to fill the gap left by the chopping, while Fig. 6 shows the waveforms which appear at the various similarly labelled points of the circuit of Fig. 5. The speech wave (A) from the microphone **1** is applied to the marker pulse generator **6** which produces a pulse (C) at the initial instant of each pitch period. The resulting period marker pulses are converted by the low-pass filter **17** into a slowly-varying pitch voltage (D) which is directly proportional to the repetition rate of the period pulses (C). This pitch voltage (D) determines the rate of change of the sawtooth output wave (E) of a writing sweep generator **64** whose sweeps are initiated by the period pulses (C). The result is a sawtooth wave that has a constant amplitude, starts with a period pulse, and has the same period as the fundamental voice period. This is the signal that determines the writing rate of the beam **61** of the tube **60**. A divider **65** reduces the recurrence rate of the period pulse train (C) by a factor N, so that at its output (F) a pulse appears for every N pitch pulses (C). Each output pulse (F) of the divider **65** operates the multivibrator **10** and so opens the gate **5** to admit the resulting chopped speech wave (B) to the grid of the tube **60**, thus to modulate the writing beam **61**. At the same time it initiates the sweep (G) of a reading sweep generator **66** which may be a duplicate of the writing sweep generator **64**, except for its sweep speed. As in the case of Fig. 1, the gate **5** is opened by each of the pulses (F) for exactly one period of each N periods and is then closed by the next one of the period pulses (C). A low-pass filter **67** controls the rate of decay of the reading sweep wave (G). The various electrodes and the erasing mechanism of the storage tube **60** are to be connected to suitable voltages and circuits to insure proper operation. The curve (H) shows the retained portions of the speech wave, stretched in time, as they appear at the output terminal of the mosaic target anode **63** of the tube **60**. Associated apparatus for chopping an aperiodic speech wave, not shown in Fig. 5, may be identical with that of Fig. 1.

The operation of restoring the original time scale to the chopped and stretched speech can likewise be accomplished with an electronic storage tube **70** and associated circuits shown in Fig. 7 that are very similar to those described above in connection with the electronic stretcher of Fig. 5. This system employs the writing beam **71** of the storage tube **70** to record the signal incoming at the terminal **21** as a charge pattern on the mosaic of a target **73** at a rate that is so adjusted that one period of the input signal extends across the target. At the instant that the writing beam **71** starts to write each period, the reading beam **72** starts to read the previous period at N times the writing rate. Although these two electron beams start their sweeps at the same location at the same time, the reading beam **72** moves N times as fast as the writing beam **71**, and there is no interference between them. The storage tube reading beam **72** should produce a destructive read-out by discharging the elements of the target mosaic **73** so that the record of each period is erased prior to the writing of the next period. Because the period being read is prior to the period being received and recorded, there is a delay of one stretched period between the reception of a stretched period and its reproduction with a restored time scale.

The controls for this tube operate as follows. Referring to the waveform diagram, Fig. 8, the curve (J) shows the stretched wave as received. It is the same as the curve (H) of Fig. 6. The marker pulse generator **26** produces a pulse (K) at the inception of each stretched pitch period. These pulses initiate the sweeps of a writing sweep generator **74** and a reading sweep generator **75**. A low-pass filter **23** converts the train of marker pulses (K) into a voltage (L) that is proportional to their repetition rate; i. e., to the pitch of the original speech signal. This pitch voltage (L) from the low-pass filter **23** controls the run down rate of the writing sweep generator **74** so that it produces a sawtooth wave (M) that has a constant amplitude and is initiated by the pitch pulses (K). The reading sweep of the generator **75** is likewise initiated by the pitch pulses (K), and the sweep rate is controlled by the output (L) of the low-pass filter

23. The reading sweep generator **75** produces a sawtooth wave (P) that has N times the slope of the writing sweep generator wave (M). The result is a target current (Q) derived from the discharge of the mosaic of the target **73** of the tube **70** which reproduces the input signal with a new time scale that is N times the original one.

The reading sweep generator **75** and the writing sweep generator **74** may be conventional, as shown in Fig. 9. A capacitor **77** is charged through a cathode follower **78** to a preassigned voltage by each marker pulse (C, F or K) and it is allowed to discharge through the high variational impedance of a pentode **79** that is connected as a constant current load. The magnitude of the equivalent constant current is approximately proportional to the pitch voltage, (D or L) applied to the control grid of the pentode **79**. In this manner the capacitor **77** discharges uniformly, and the rate of change of its voltage during discharge is proportional to the pitch of the speech wave. The only difference between the reading sweep generator and the writing sweep generator is that the capacitor in the writing sweep generator **74** is N times as large as that of the reading sweep generator **75**. With appropriate changes in the capacitance of the capacitor **77**, Fig. 9 also shows the circuit details for either the writing sweep generator **64** or the reading sweep generator **66** of Fig. 5.

If desired, the above system can be modified to reduce the delay by one period in the unstretched speech by initiating the sweep of the reading beam **71** when the writing beam **72** has completed a fraction

$$\frac{N-1}{N}$$

of its excursion across the target **73**. In this manner the reading beam **72** completes its reading operation of each period at the same instant that the writing beam **71** completes writing that same period. This can be accomplished by initiating the reading sweep from an amplitude discriminator that indicates when the writing sweep has completed the fraction

$$\frac{N-1}{N}$$

of its excursion.

As indicated above, a speech wave is almost periodic in character, which means that each of its periods is almost, but not quite, the same in form as the prior period. The departure from exact similarity represents a gradual change in any or all the features of the wave, namely, the phase distribution as between its components, the duration of the period on the time scale, and its amplitude or power. The apparatus described above constructs artificial waves each of which is the properly weighted sum of an earlier wave period and a later one. Hence, it takes all of these gradually changing features into account.

Experiments have shown that the amplitude or power of the speech wave is its property which changes most rapidly and which, therefore, is chiefly responsible in the change in the wave from each period to the next. In accordance with the invention in another of its aspects this one source of change is utilized to control reconstruction of artificial speech, the others being disregarded. This embodiment, which makes for simplification of the apparatus, may be instrumented as shown in Fig. 10, where a speech wave originating, for example, in a microphone **1** is passed through a variolosser **80**, preceded and followed by amplifiers **81, 82**. The output of the second amplifier **82** is passed through a rectifier **83** and a low-pass filter **84** to provide a slowly varying control current for application to the variolosser to adjust the magnitude of the impedance which it interposes in the voice path. These elements constitute a conventional volume compressor, and the control current derived from the output terminal of the low-pass filter **84** may also serve, in the fashion to be described, as a measure of the instantaneous amplitude or power of the original speech. To this end it is transmitted over an auxiliary channel **85**.

The compressed output of the amplifier **82** is then chopped in the fashion described in connection with Fig. 1, and through the action of like apparatus, with a chopping factor N as determined by the construction of the divider **8**. The chopped speech may now be stretched in time as by a stretcher **14** or otherwise modified to take advantage of the chopping action. It is next transmitted over a medium **19** to a receiver station. There it is first restored to its original dimensions on the time scale through the agency of a time scale restorer **22** controlled by a marker pulse generator **26** as described in connection with Fig. 1. At the output point of the time scale restorer **22** one period out of every N periods appears, and it is the function of the apparatus to be described to insert, in the remaining $N-1$ blank intervals, repetitions of the prior received period modified only as to their amplitudes. The successive repetitions may be constructed much as described in connection with Fig. 1 by applying the chopped speech output of the time scale restorer **22** to a sequence of $N-1$ delay devices. Thus, in the illustration in which $N=3$, two such delay devices, **86*a*, 86*b*** are shown. The delay which each one of them introduces is equal to a single fundamental period of the speech wave, and these delays must therefore be continuously varied as the period or pitch of the speech varies. To this end, they are shown as under the control of the output of the marker pulse generator **26**, smoothed to a slowly varying pitch voltage by the filter **23**. The actual apparatus by which this pitch voltage adjusts the delays in proportion to the speech wave period may be similar to that shown in Fig. 1.

The output of the time scale restorer **22** is applied through an adding network **86** to an amplifier **87** (*a*) without delay, (*b*) after a delay of one fundamental period and (*c*) after a delay of two fundamental periods. The output of this amplifier **87** thus includes, following each wave actually received, two successive repetitions of it. These waves are now applied to a volume expandor **88** which operates to expand the volume range of the signal applied to it to the same extent as that by which the volume range of the original speech was compressed by the variolosser **80**, at the transmitter station. One convenient way of achieving this result is to provide a negative feedback amplifier **89** having in its feedback path a variolosser **90** identical with the variolosser in the forward path of the compressor at the transmitter station. The impedance interposed by this variolosser **90** is adjusted by, and is under the continuous control of, the amplitude control signal transmitted by way of the auxiliary channel **85**.

The output signal of the amplifier **89** may now be applied by way of a suitable coupling transformer to a sound reproducer **42**.

It is a feature of the apparatus shown in Fig. 10, and especially of the employment of a compressor-expandor combination therein, that the auxiliary amplitude control signal may be continuously applied to the entire output of the amplifier **89** including received periods as well as repeated periods. If preferred, and at the cost of some further complexity of the apparatus, the compressor **80** and the expandor **88** may be dispensed with and each received period may be reproduced without change, the auxiliary volume control signal being applied exclusively to the $N-1$ artificial repretitions of each received period.

The first form of the invention shown in Fig. 1, with or without the refinements thereof shown in Figs. 3 to 9, inclusive, comprises a linear or first order interpolator. The interpolation principle embodied in these figures may evidently be extended in two or more different ways:

First, it may be extended to include interpolation of the second or a higher order simply by appropriate modifications and extensions of the weighting network 40. Second, it may be extended to include interpolation based, not merely on the immediately preceding and following periods, but on still earlier and later periods as well. This extension, which provides higher precision of the reconstructed wave, may be effected by appropriate modifications and extensions of the delay and control circuits, as well as the weighting network.

Furthermore, the two principal forms of the invention shown in Figs. 1 and 10, respectively, are not to be taken as mutually exclusive. Situations may arise in which it is of advantage to supplement the action of an interpolator, for example, a first order interpolator as shown in Fig. 1, with an auxiliary amplitude control signal as shown in Fig. 10. Such a combination is within the contemplation of the invention.

What is claimed is:

1. Speech transmission apparatus which comprises a source of a speech wave consisting of a sequence of wave portions, means for eliminating certain individual ones of said portions to leave blank intervals, means for transmitting to a receiver station wave portions preceding and following each blank interval, means for developing, at said receiver station, a sequence of artificial wave portions of which the amplitudes follow the amplitude variations of the original speech waves, and means for intercalating at least one of said artificial wave portions in each blank interval, thereby to reconstruct said original wave.

2. Speech transmission apparatus which comprises a source of a speech wave consisting of a sequence of wave periods, means for eliminating certain individual ones of said periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means for developing, at said receiver station, a sequence of artificial wave periods, means for causing the amplitudes of said artificial wave periods to follow the amplitude variations of the original speech wave, and means for intercalating said sequence in each blank interval, thereby to reconstruct said original wave.

3. Speech transmission apparatus which comprises a source of a speech wave consisting of a sequence of wave periods, means for eliminating certain individual ones of said periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means for developing, at said receiver station, artificial, wave periods each of which is a weighted sum of a preceding and a following transmitted wave period, and means for intercalating at least one wave of said sequence in each blank interval, thereby to reconstruct said original wave.

4. Speech transmission apparatus which comprises a source of a speech wave consisting of a sequence of wave periods, means for eliminating N—1 of each group of N successive ones of said periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means for developing, at said receiver station, a sequence of N—1 artificial wave periods $P_a$, $P_b$, $P_c$ . . . $P_{N-1}$, means for proportioning said artificial wave periods in accordance with the formulae:

$$P_a=\frac{N-1}{N}P_1+\frac{1}{N}P_2$$

$$P_b=\frac{N-2}{N}P_1+\frac{2}{N}P_2$$

$$P_c=\frac{N-3}{N}P_1+\frac{3}{N}P_3$$

$$\cdot = \cdot\ \cdot\ \cdot\ \cdot\ \cdot$$

$$\cdot = \cdot\ \cdot\ \cdot\ \cdot\ \cdot$$

$$P_{N-1}=\frac{1}{N}P_1+\frac{N-1}{N}P_2$$



wherein $P_1$ represents the period immediately preceding a blank interval and $P_2$ represents the period immediately following said blank interval, and means for intercalating said artificial wave periods sequentially in each blank interval, thereby to reconstruct said original wave.

5. Speech transmission apparatus which comprises a source of a speech wave consisting of a sequence of wave periods, means for developing an auxiliary signal proportional to the amplitude of said speech wave, means for eliminating certain individual ones of said periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means for also transmitting said auxiliary signal, means for developing, at said receiver station, a sequence of artificial wave periods, each of which is a substantial repetition of the preceding transmitted wave period, means for varying the amplitudes of said repetitions under control of said auxiliary signal, and means for intercalating at least one of said repetitions in each blank interval, thereby to reconstruct said original wave.

6. Speech transmission apparatus which comprises a source of a speech wave comprising a sequence of wave periods, means for eliminating from said sequence $N-1$ of each group of N successive ones of said wave periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means, at said receiver station, for developing for each blank interval and from the transmitted waves which precede and follow said blank interval a group of $N-1$ artificial wave periods, means for proportioning said several artificial wave periods as variously weighted sums of said preceding and following wave periods, and means for intercalating said artificial wave periods in said blank interval.

7. Speech transmission apparatus which comprises a source of a speech wave comprising a sequence of wave periods, means for eliminating from said sequence $N-1$ of each group of N successive ones of said wave periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means, at said receiver station, for mixing the transmitted waves which precede and follow each of said blank intervals in various proportions, to form a group of $N-1$ artificial wave periods, means for arranging said artificial wave periods in order of increasing emphasis of the following wave and decreasing emphasis of the preceding wave, and means for intercalating said ordered artificial wave periods in said blank interval.

8. Speech transmission apparatus which comprises a source of a speech wave comprising a sequence of wave periods, means for eliminating from said sequence $N-1$ of each group of N successive ones of said wave periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means, at said receiver station, for developing for each blank interval and from the transmitted wave which precede and follow said blank interval a group of $N-1$ artificial wave periods, means for proportioning said several artificial wave periods as variously weighted sums of said preceding and following wave periods, means for variously delaying each of said artificial wave periods by an integral number of fundamental pitch periods of said speech wave to form a sequence of artificial wave periods, the members of which sequence differ progressively from end to end of said sequence, and means for intercalating said sequence in said blank interval.

9. Apparatus as defined in claim 8 wherein said delayed means comprises $2N-2$ delay devices, coupled together in tandem, means for applying each received wave to the input terminal of the first of said devices, means for deriving a delayed wave from the output terminal of each of said devices, and means for additively combining said delayed waves.

10. In combination with apparatus as defined in claim 9, means for deriving a period control signal from received waves, and means for adjusting the propagation length of each of said delay devices under control of said period control signal to introduce a delay equal to the fundamental period of said speech wave.

11. Speech transmission apparatus which comprises a source of a speech wave comprising a sequence of wave periods, means for eliminating from said sequence $N-1$ of each group of N successive ones of said wave periods to leave blank intervals, means for developing an auxiliary signal representative of the changing character of said speech wave, means for transmitting to a receiver station wave periods preceding and following each blank interval, means for also transmitting said auxiliary signal to said receiver station, means, at said receiver station, for developing for each blank interval and from the transmitted wave which precedes said blank interval a group of $N-1$ artificial repetitions of said preceding transmitted wave, means for variously delaying each of said repetitions by an integral number of fundamental pitch periods of said speech wave to arrange said repetitions in an ordered sequence, means for varying the amplitudes of said repetitions under control of said auxiliary signal, whereby the members of said sequence differ progressively from end to end of said sequence, and means for intercalating said sequence in said blank interval.

12. Apparatus as defined in claim 11 wherein said delaying means comprises $N-1$ delay devices, coupled together in tandem, means for applying each received wave to the input terminal of the first of said devices, means for deriving a delayed wave from the output terminal of each of said devices, and means for additively combining said delayed waves.

13. In combination with apparatus as defined in claim 12, means for deriving a period control signal from received waves and means for adjusting the propagation length of each of said delay devices under control of said period control signal to introduce a delay equal to the fundamental period of said speech wave.

14. Speech transmission apparatus which comprises a source of a speech wave comprising a sequence of wave periods, a volume-range compressor for said waves, means for deriving from said compressor an auxiliary signal representative of the amplitude variations of said speech wave, means for eliminating from said sequence $N-1$ of each group of N successive ones of said wave periods to leave blank intervals, means for transmitting to a receiver station wave periods preceding and following each blank interval, means, at said receiver station, for developing for each blank interval and from the transmitted wave which precedes said blank interval, a group of $N-1$ repetitions of said preceding wave, means for variously delaying said repetitions by an integral number of fundamental pitch periods of said speech wave to form a sequence of artificial wave periods, means for intercalating said sequence in said blank interval to form a reconstructed wave of compressed volume range without blank intervals, and means for varying the amplitude of said reconstructed wave under control of said auxiliary signal.

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UNITED STATES PATENT OFFICE

**Certificate of Correction**

Patent No. 2,860,187 November 11, 1958

Edward E. David, Jr., et al.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 11, lines 68 and 69, the formula should appear as shown below instead of as in the patent:

$$P_c=\frac{N-3}{N}P_1+\frac{3}{N}P_2$$

Signed and sealed this 17th day of March 1959.

[SEAL]

Attest:
KARL H. AXLINE,
*Attesting Officer.*

ROBERT C. WATSON,
*Commissioner of Patents.*