Dec. 26, 1961 G. RAISBECK 3,014,985

SMOOTHING OF RECTANGULAR WAVES

Filed May 22, 1959 4 Sheets-Sheet 1

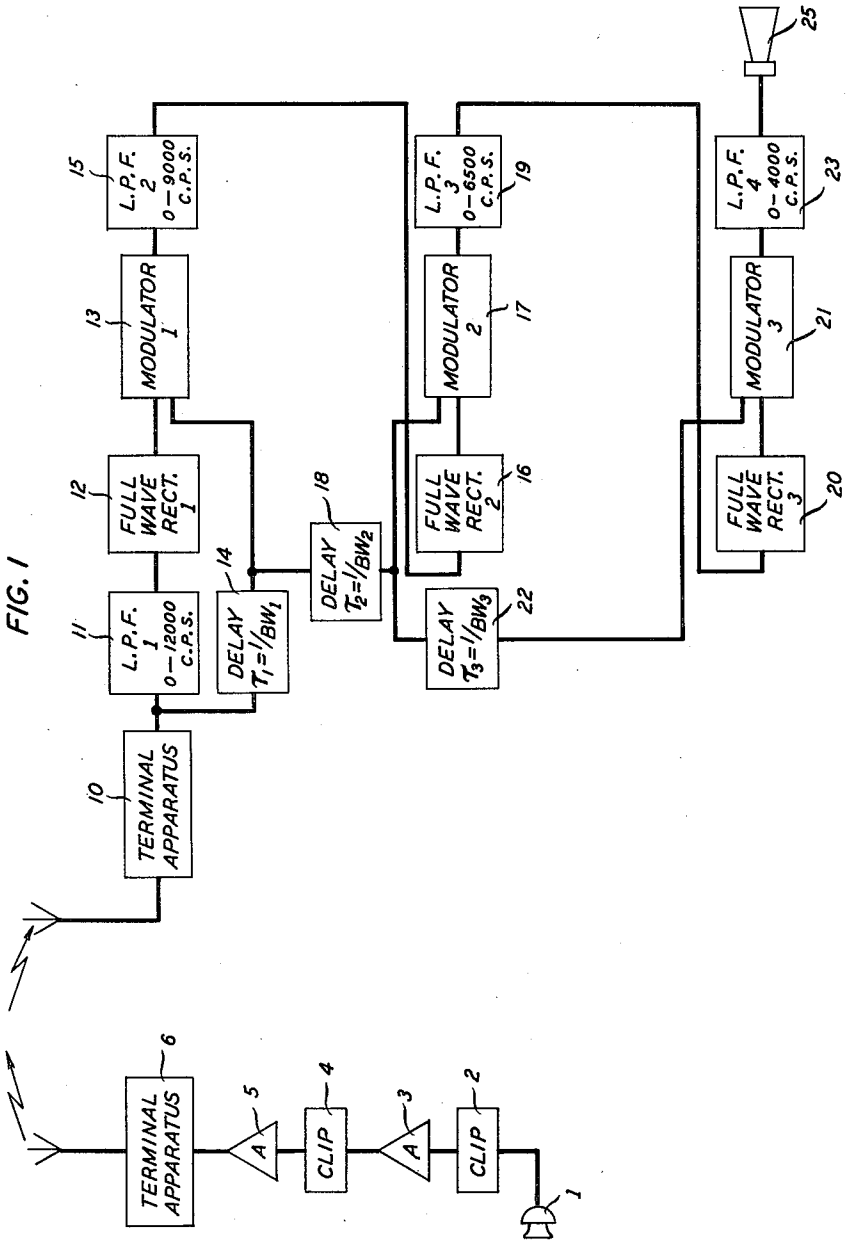


FIG. 1

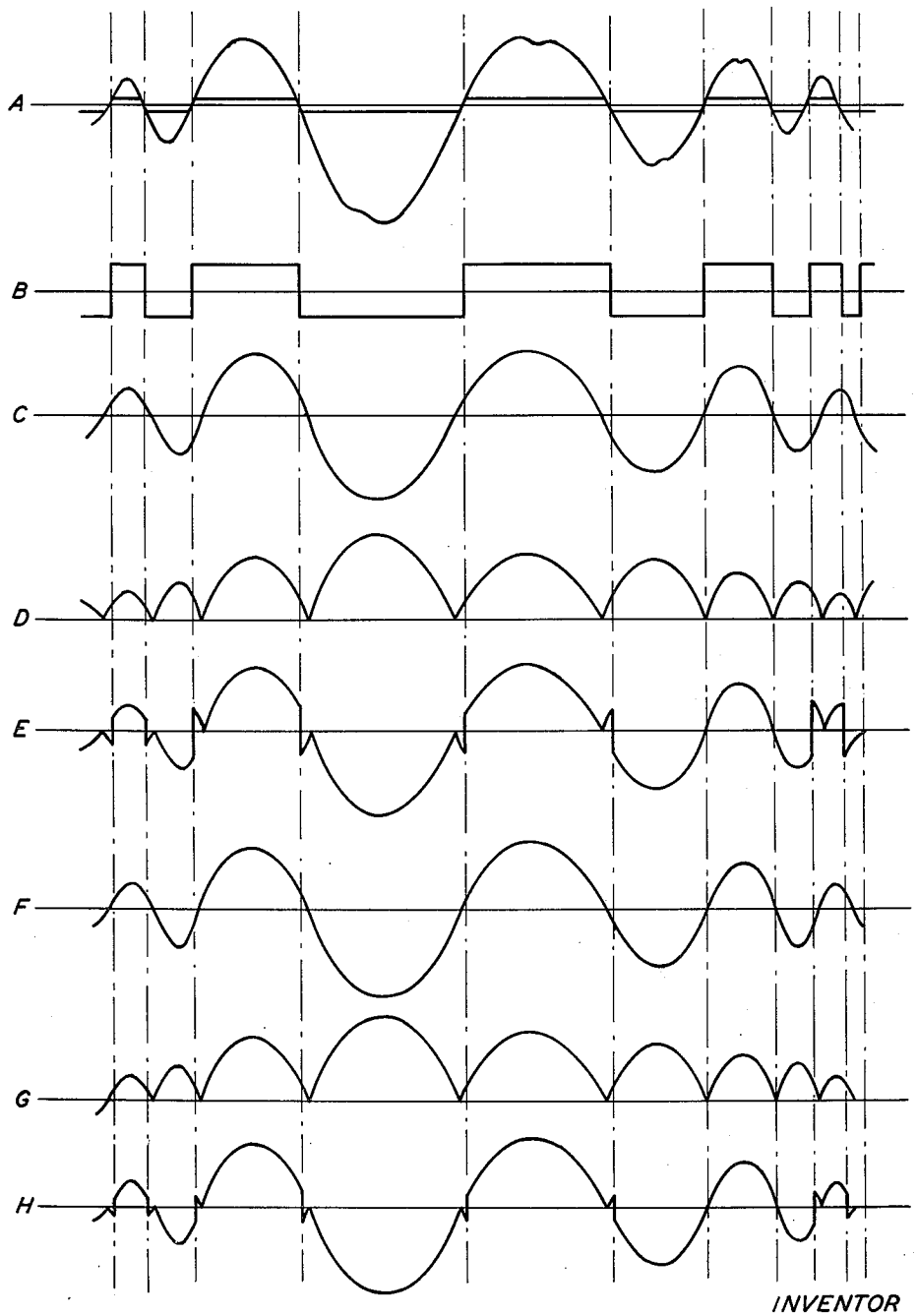
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SMOOTHING OF RECTANGULAR WAVES

Filed May 22, 1959 4 Sheets-Sheet 2

FIG. 2



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SMOOTHING OF RECTANGULAR WAVES

Filed May 22, 1959 4 Sheets-Sheet 3

FIG. 3

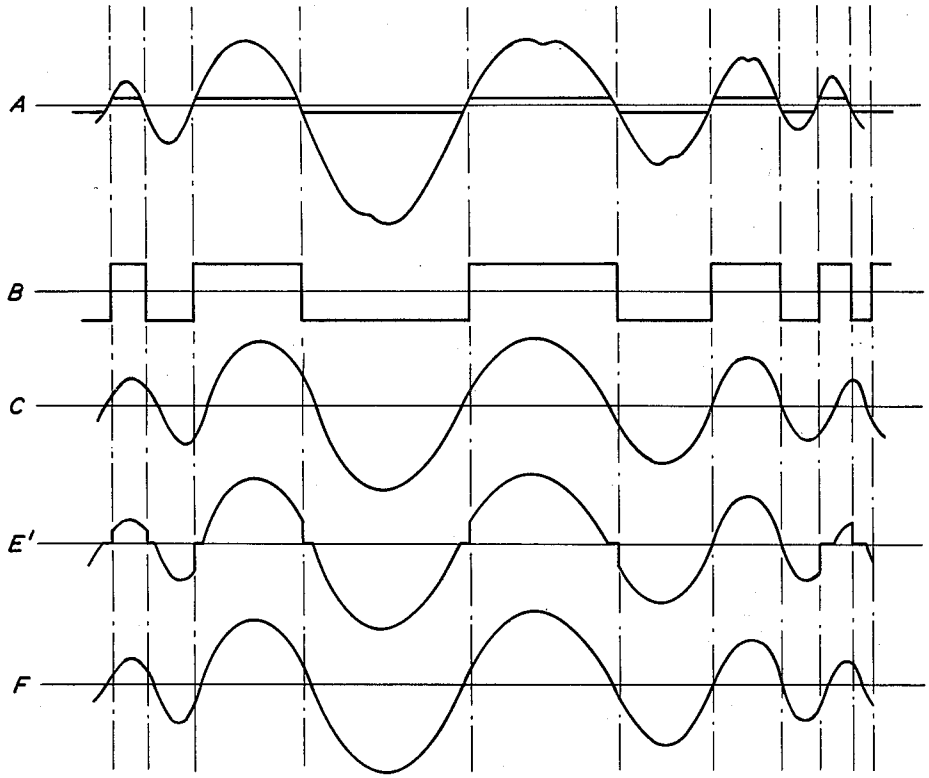
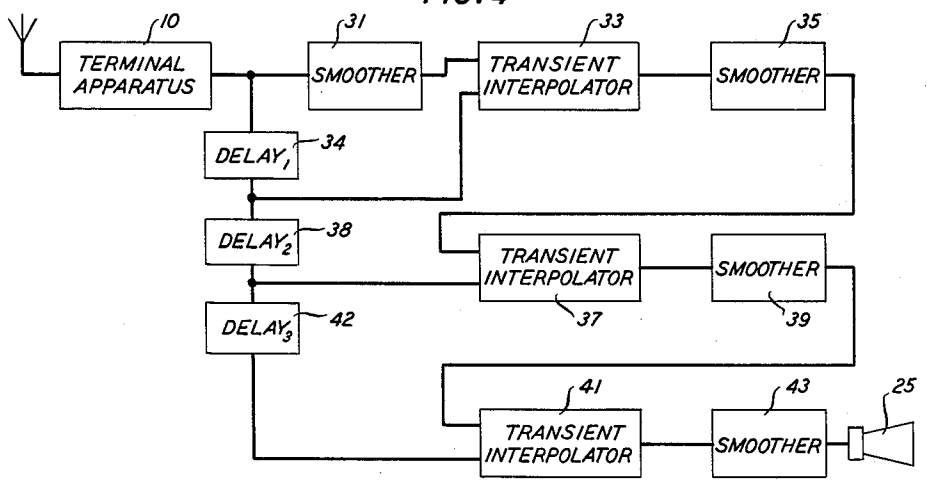


FIG. 4



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SMOOTHING OF RECTANGULAR WAVES

Filed May 22, 1959 4 Sheets-Sheet 4

FIG. 5

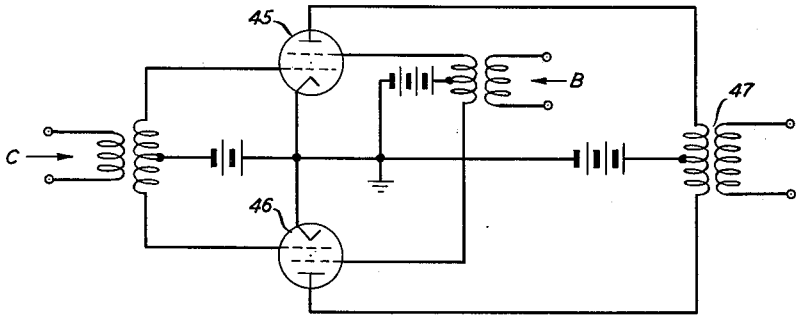
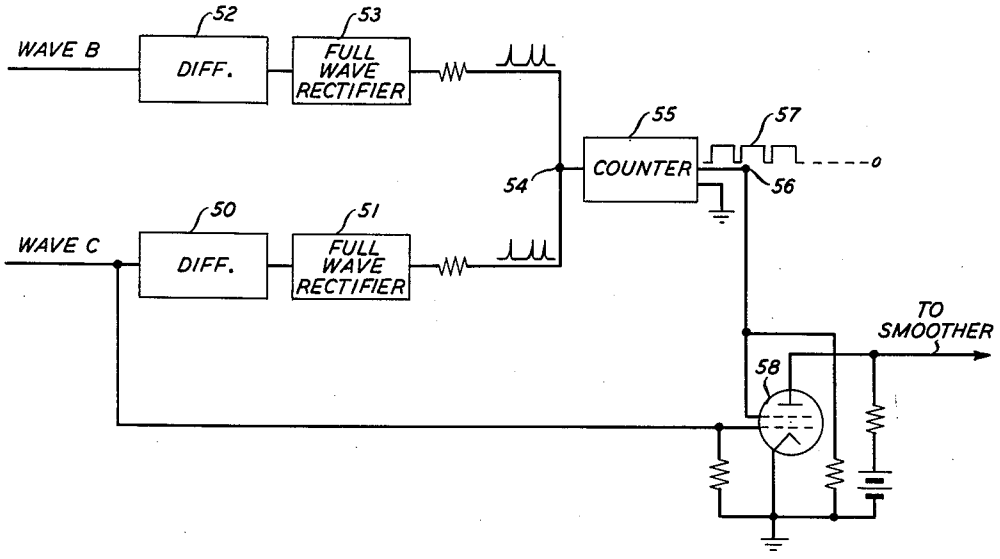


FIG. 6



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3,014,985

SMOOTHING OF RECTANGULAR WAVES

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Filed May 22, 1959, Ser. No. 815,115
15 Claims. (Cl. 179—1)

This invention deals with the smoothing of rectangular waves. Its principal object is to recover a smooth band-limited wave, closely resembling a voice wave and suitable for audible reproduction as by a telephone receiver, from a sharp-cornered rectangular wave derived, for the sake of transmission advantages, from an original voice wave.

To secure certain economies in transmission it has already been proposed, notably by R. L. Miller in his application Serial No. 613,886, filed October 4, 1956, and now matured into Patent 2,953,644, granted September 20, 1960, to break a speech wave down into two factors, namely a phase or frequency factor and an amplitude or envelope factor, to generate signals that are individually representative of these factors, and to transmit these factor waves to a receiver station over independent channels each of which is respectively tailored to suit the characteristics of its factor wave. To secure the maximum advantage in the transmission of the phase or frequency factor wave from the standpoint of immunity to noise, regenerability and the like, it may be derived from the original speech wave by a sharp clipping process that develops a sequence of flat-topped pulses of varying durations and of alternately opposite polarities: a wave in which the axis crossing instants or zeros of the original wave on the time scale are preserved but all information as to amplitudes is discarded. At the receiver station, this flat-topped wave may be modulated in amplitude by the envelope factor wave that arrives by way of an independent channel.

The outcome of the modulation process is still, however, a wave each of whose parts is a rectangle having sharp corners. These sharp corners represent distortion products originally acquired in the course of the clipping process, and they cause the reproduced speech to have an unpleasant raucous sound. To improve the quality of the reproduced speech it has been proposed to pass it through a filter of the low-pass or band-pass variety proportioned to pass all frequency components present in the original speech but to exclude the high frequency components of the rectangular wave that are introduced by the clipping process. The filter thus results in rounding the sharp corners of each rectangular portion of the clipped wave. Unavoidably, however, it also shifts the locations of the zeros of this wave on the time scale.

Recent investigations of clipped speech as reported, for example, by Irwin Pollack and J. M. Pickett in a monograph entitled "Intelligibility of Peak-Clipped Speech at High Noise Levels," published in the Journal of The Acoustical Society of America for January 1959, vol. 31, page 14, have indicated that the intelligibility of clipped speech, even without smoothing, is surprisingly high, though its quality and naturalness are poor; that, indeed, at certain noise levels, its intelligibility is higher than that of the original speech. It is inferred that a disproportionately large amount of meaning-bearing information is concentrated in the coordinated locations on the time scale of the successive zeros of a speech wave, while the amplitude variations of the speech wave, lost in the clipping process, carry, in contrast, information that is rather of a quality-determining character. It follows that any shifting of these meaning-determining zeros that is uncoordinated with the speech wave itself, as by a smoothing filter introduced to improve quality, should

reduce intelligibility. This has been found to be the case in practice: the improvement of the quality of a clipped speech wave merely by filtering to round its corners is achieved at the price of substantial reductions of its intelligibility; and it appears that the reduction of intelligibility stems from the displacement of the zeros from their proper positions on the time scale through the action of the filter.

Accordingly, it is a more specific object of the present invention to derive from a substantially rectangular clipped speech wave a smooth band-limited wave while retaining each of its zeros at its correct location on the time scale. The invention accomplishes this object by a process, advantageously repeated several times in succession, comprising four different steps, taken in order. First, the rectangular wave is filtered to remove modulation products that lie above the voice frequency band and so to round its sharp corners. This step may be carried out by a conventional low-pass filter and it inevitably results in shifting the zeros. Second, each negative swing of the smoothed wave is inverted as by a full wave rectifier. In the resulting wave each zero crossing of the filtered wave is replaced by a cusp so that while, in the filtered wave the polarity changes abruptly at each zero, in the rectified wave the polarity remains unchanged but the slope changes abruptly. The rectification process does not further displace the zeros on the time scale. Third, a new set of zeros, correctly located on the time scale, are artificially introduced. Advantageously, the introduction of the new zeros is effected in such a way that the rectified wave changes in polarity abruptly at each one of them, leaving a sharp, brief transient condition between each of the correct new zeros and the corresponding displaced original zero. This step may conveniently be carried out by intermodulating the rectified wave, whose zeros are displaced, with the original rectangular wave whose zeros are correctly located. This step can readily be instrumented with an amplitude modulator. Fourth, the wave output of the modulator is again filtered to remove modulation products lying outside of the speech band. This second filtering process effectively introduces a smooth wave portion that cuts through each of the transient portions of the modulated wave, substituting a single zero crossing for each pair of zeros of the modulated wave. This zero crossing lies at a point on the time scale that is intermediate between each original displaced zero (a cusp of the rectified wave) and the corresponding new correctly located zero that was introduced by the modulation process. As a result, this newly filtered wave is not only as smooth as the first filtered wave but also, more significantly, each of its zeros lies closer to its correct location than does the corresponding zero of the first filtered wave.

This sequence of operations, with the exception of the first one, may advantageously be repeated several times and each repetition moves the zeros closer to their correct locations. Hence the result of a suitable number of such repetitions produces a smooth, band-limited wave in which all the zeros are correctly located and in which, therefore, the high intelligibility of the clipped speech wave is in no way reduced.

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

FIG. 1 is a schematic block diagram of apparatus embodying the invention;

FIG. 2 is a set of waves illustrative of the operations of the apparatus components of FIG. 1;

FIG. 3 is a set of waves illustrative of the operations of the apparatus of the invention in a more general form;

FIG. 4 is a schematic block diagram showing apparatus for processing the waves of FIG. 3;

FIG. 5 is a schematic circuit diagram of a transient interpolator suitable for use as a component of the apparatus of FIG. 4; and

FIG. 6 is a schematic block diagram showing an alternative to the interpolator of FIG. 5.

Referring now to the drawings, a complex wave such as a speech wave originating, for example, in a microphone **1** is applied to a clipper **2** whose function is to derive from the speech wave a clipped wave in which each zero crossing of the speech wave is accurately preserved, while each excursion of the speech wave, positive or negative, is replaced by a rectangular wave portion of preassigned fixed amplitude. The clipping process is illustrated in curve A of FIG. 2 wherein the continuous line represents a typical portion of an original speech wave and the broken line represents its clipped counterpart. Evidently, the clipped wave follows the original wave throughout a brief course including each zero crossing and, throughout this course, it has a finite slope. To produce as nearly as possible a fully rectangular wave, the clipping operation may advantageously be repeated several times with amplification between each individual clipping operation and the next. To this end the clipper **2** of FIG. 1 is followed by an amplifier **3**, a second clipper **4** and a second amplifier **5**. The output wave of this apparatus is thus a rectangular wave as illustrated in curve B of FIG. 2.

In accordance with the invention this clipped speech wave is transmitted to a receiver station by any technique deemed appropriate, instrumented by terminal apparatus **6**, and preferably over a transmission medium designed or selected with a view to preserving the abrupt transitions of the wave of curve B and with no especial regard for its capacity to transmit large amplitudes.

At the receiver station the incoming clipped speech wave, after any preliminary processing called for by the vehicle of transmission and indicated as being carried out by terminal apparatus **10**, is first applied to a filter **11**. The passband of this filter should extend from the lowest component frequency of the speech wave at least to its highest component and, for a reason to appear below, preferably considerably higher. It high frequency cutoff, however, should lie below that part of the frequency scale in which are concentrated the high frequency modulation products introduced by the clipping operation and appearing as the sharp corners of the wave of curve B.

The output of this filter (curve C) is evidently much smoother than the rectangular wave of curve B; but each zero crossing of curve B has been displaced in curve C, from its proper location on the time scale and to an extent dependent largely on the length of the rectangular block of the curve B which precedes it.

The smoothed wave, curve C, if applied directly to a reproducer would be of higher quality than the rectangular wave of curve B but, because of the displacement of those zeros, of reduced intelligibility. In accordance with the invention the next step is to invert every negative excursion of the wave C. This may be done by applying the wave C to a full wave rectifier **12** of conventional construction. Its output wave, curve D, duplicates each positive excursion of the wave C and replaces each negative excursion by its inverted replica. Thus, each zero crossing of the wave of curve C is replaced, in curve D, by a zero cusp at which the slope of the wave changes abruptly though its amplitude does not.

If preferred, the rectifier **12** may of course be poled to invert positive portions of the wave of curve C, leaving its negative portions unchanged. The result would be an inverted wave that is a mirror image of the wave of curve D, reflected in the horizontal axis.

The next step is to interpolate, in the wave of curve D, a new artificial set of zeros that are correctly located on the frequency scale, and preferably zeros that are zero crossings, in contrast to zero cusps. This step may conveniently be carried out by modulating the wave of curve D with the original rectangular wave, curve B. To this end there is provided a modulator **13** having two input points, to one of which the rectified wave, curve D, is applied while a delayed replica of the clipped wave, curve B, is applied to the other. The delay, which serves to compensate unavoidably introduced by the filter **11**, and hence may be equal to the reciprocal of its bandwidth, is provided by an all-pass delay device **14**. The output of the modulator **13**, curve E, retains the zero cusps of curve D, some of them being inverted; and it includes a new set of correctly located zeros, each of which is a zero crossing. Evidently, each displaced zero cusp is spaced from the correctly located zero from which it was derived by a sharp transient which includes both an abrupt change in polarity and an abrupt change in slope, both introduced by the modulation step.

In the preparation of FIG. 2 the delay inevitably introduced by the first filter **11** and the compensating delay introduced into the rectangular wave by the delay device **14** prior to its application to the modulator **13** have both been disregarded. As a result the zero crossings of the original message wave, curve A, and of its clipped counterpart, curve B, are brought into alignment throughout the entire group of curves. Such alignment facilitates the exposition of the mode of operation of the invention. In practice, of course, each of these delays must be taken into account; and a presentation of the resulting waves on a real time scale would include a slight uniform shift of the entire filtered wave to the right in the figure. It would also include a sequence of rectangular modulating waves, each slightly and uniformly shifted to the right as compared with its predecessor. All of such shifts have been omitted from FIG. 2 in the interests of clarity.

The next step is to smooth the wave E in a fashion to remove these sharp transients. To this end the wave E is passed through a filter **15** which, like the first filter **11**, is proportioned to pass the component frequencies of the voice wave but to exclude the higher modulation products. In graphical terms, this process substitutes a smooth wave portion, curve F, for each transient as indicated in broken lines on the curve E. Evidently this smoothed portion includes a single zero crossing, located at a point on the frequency scale that lies between the correctly located zero crossing artificially introduced and the original displaced zero represented by the adjacent cusp.

The resulting wave, curve F, is characterized by a single zero crossing for each zero crossing of the original wave, displaced from its correct position, but less so than that of the wave C. Moreover, all cusps of the wave E have been removed from the wave F by the second filtering operation. Thus, the intelligibility of the wave F, measured by the location of its zeros, is improved as compared with that of the wave of curve C while, because it is no less smooth, its quality is no more degraded.

The foregoing process is advantageously repeated as many times as may be desired. Curve G shows the output of a second full wave rectifier **16** to which the wave G is applied and curve H shows the output of a second modulator **17** to which are applied the wave G and the original rectangular wave, again delayed by the reciprocal of the bandwidth of the filter **15**, as by an all-pass delay device **18**. Like the curve E, the curve H includes pairs of zeros, one member of each pair being correctly located and represented by a zero crossing and the other being a displaced cusp. Comparison of curve H with curve E shows, however, that each of the transients that is included between the two members of each such zero pair is of briefer duration than the corresponding transient of the curve E. Hence a smoothing operation carried out by a third filter **19** to remove these transients replaces each zero pair by a single zero crossing that lies between

the correct location of the artificial zero and the incorrectly located neighboring cusp.

After a sufficient number of repetitions of the entire process, indicated as being carried out by a third rectifier **20**, modulator **21**, delay device **22** and filter **23**, each of the transients becomes vanishingly small and the smooth wave portion that cuts through each such transient includes a zero crossing that lies as close to the correct location as may be desired. The resulting wave may now be applied to a reproducer **25**.

In order that this iterative process shall converge in the fashion described above it is necessary that each zero crossing of the first filtered wave shall be displaced from its correct location by less than one half the time interval between any two correctly located zeros. With this proviso the two members of each zero pair, curve E or curve H, lie closer together on the frequency scale than do any two unrelated zeros, and the transient to be removed by the ensuing filtering operation lies between two related zeros instead of between two unrelated ones.

To insure that the foregoing condition shall be met it is only necessary to provide that the initial filter shall have a sufficient bandwidth, e.g., that its high frequency cutoff shall be located on the frequency scale in the neighborhood of the second or third harmonic of the highest frequency component of the original message wave to be reproduced. Of course, with a filter of such a broad band, the smoothing that it introduces is somewhat restricted. This, however, is of small consequence because of the fact that successive smoothing operations are contemplated.

Once the foregoing proviso has, by proper proportionment of the first filter **11** been met, the second filter **15** may evidently have a narrower passband; i.e., it may be so proportioned that its high frequency cutoff lies at a lower point of the frequency scale than does that of the first filter. Thus it can safely introduce more smoothing than does the first filter and, in general, each filter of the sequence can have a narrower passband than its predecessor.

From what has been said it will be evident that the essential is to introduce, into the smoothed wave C, a set of correctly located artificial zeros in a manner such that between each one of them and the corresponding displaced original zero a transient exists, as illustrated in the wave E, of a nature such that the following smoothing operation removes the transient, providing a smooth wave having a single zero lying between the two members of each zero pair.

The rectification operation, curve D, is responsible for the sharply peaked character of the transients, curve E. Under some circumstances the substantial amplitudes of such transients may more than offset the fact that their component frequencies lie, for the most part, outside the passband of the following filter. In such circumstances it may be preferable to generate transients of zero amplitude.

More specifically, and referring to FIG. 3 curves A, B and C are identical with those of FIG. 2. Curve D of FIG. 2, representing the rectification operation, is omitted and, instead of curve E with its sharp transients, curve E′ shows a wave having transients of zero amplitude, one such transient interconnecting each artificial interpolated zero with the zero original displaced zero. Curve F is again the same as curve F of FIG. 2, and contains a single zero for each zero pair of curve E′ and lying approximately midway between them; i.e., at the midpoint of the zero-amplitude transient. Repetitions of the process for further improvement of the wave, indicated in FIG. 2 by curves G and H, are to be understood in FIG. 3.

FIG. 4 shows three-stage apparatus which is broadly similar to that of FIG. 1, differing principally in that the rectifiers **12**, **16** and **20** are absent and the modulators **13**, **17** and **21** are replaced by transient interpolators **33**, **37** and **41**. The delay devices **34**, **38** and **42** are included to compensate for any mean delays that may be introduced by the smoothers **31**, **35**, and **39**.

Each transient interpolator of FIG. 4 may take any of a number of different forms. A simple one is shown in FIG. 5 and consists, generally, of a double push-pull modulator. The smoothed wave C may be applied in push pull to the control grids of the two tubes, **45**, **46**, the clipped wave, curve B, being similarly applied to its screen grids. The tubes **45**, **46** are to be biased for class B operation with respect to the signal applied to the control grids and, furthermore, in such a fashion that each tube is unconditionally cut off for a negative signal applied to its screen grid. Thus, considering the upper tube **45** by way of example, positive excursions of the wave C, applied to its control grid, are passed through its anode to the output transformer **47**, but only while its screen grid is also positive by the application to it of the positive excursions of the clipped wave B. The connections being symmetrical, the same holds for the lower tube **46** with respect to negative excursions of the waves B and C. As a result, the wave applied to the output transformer **47** duplicates the wave C except for the introduction of transients of zero amplitude, curve E′ of FIG. 3, between each interpolated zero of the clipped wave B and the corresponding displaced original zero of the smoothed wave C.

In principle, the same result can be achieved in many other different ways, one of which is indicated in FIG. 6. Here the smoothed wave, curve C, is applied to a differentiator **50** and a full wave rectifier **51** connected in tandem while the clipped wave, curve B, is applied to a differentiator **52** and to a full wave rectifier **53** connected in tandem. The first rectifier **51** thus delivers a train of pulses, one for each displaced original zero, while the second rectifier **53** delivers a train of pulses, one for each true zero to be interpolated. These two pulse trains are combined additively at the input point **54** of a counter **55**, for example a bistable multivibrator, which thus delivers at its output terminal **56** a wave that is positive and of standard amplitude except during the intervals between the two members of each zero pair, when its output falls to zero. This wave being applied to the screen grid of a buffer tube **58** acts to cut the tube off and so inhibit passage of signals through it during the negative excursions of the counter output. At other times the tube may be a linear amplifier. The wave C being applied to the control grid of this tube, the signal appearing across its anode resistor has the form of curve E′ of FIG. 2 and is thus suitable for application to the second smoothing filter **35** of FIG. 4.

The apparatus of FIG. 6 depends for successful operation on discrimniation between the two members of each zero pair. Counters are well known that are capable of discriminating between pulses that are spaced apart on the time scale by a fraction of a microsecond. In the limitng case in which the pulses from the two incoming trains coincide exactly, they are superposed to produce a single pulse of twice the amplitude of either one alone. Means are well known in the art for immediately restoring a counter to its original condition in response to an input pulse of twice the normal input pulse amplitude.

The tandem connected elements of FIGS. 1 and 4 are not intended to be exclusive. In general, any repetitive operation that can be carried out by like circuit elements connected in tandem can in principle be carried out by one such element through which the information to be processed is recirculated by way of a feedback loop. Care must, of course, be exercised to prevent confusion, in such case, between two different wave portions that are circulating in the loop simultaneously, of which one originated at an earlier time and the other at a later time.

Variations in amplitude of the wave F or, if the process is repeated, variations in amplitude of the wave output of the last filter, bear only a very general resemblance

to the variations in amplitude of the original message wave. All amplitude information in the original message wave having been discarded by the clipping process, the amplitude variations of the filter output, curve F, are dependent on the filter characteristics rather than the statistics of the message wave. As above stated, its intelligibility is high. While the quality of the reproduced sound is not raucous or unpleasant it is nevertheless unnatural in the sense that it does not reflect the identity of the original speaker. If naturalness, as well as intelligibility and quality, are desired, the output of the final filter of the set may, of course, be modulated in amplitude by an envelope signal as taught by R. L. Miller in his aforementioned application.

While the invention has been illustrated as applied to a wave derived from speech by a clipping operation without intermediate processing, it is evidently applicable to any irregular rectangular wave. For example, an original speech wave may be first differentiated once or more to produce a first derivative wave or a derivative wave of higher order. Such a derivative wave may now be clipped to produce a clipped derivative wave in contrast to a clipped speech wave. The entire process of the invention as described above may now be applied to the clipped derivative wave to recover a smooth wave having the same zeros. The latter may now be integrated, once for the first derivative, twice for the second derivative and so on, to recover a smooth wave having the same zero crossings as the original message wave.

Still other variants of the illustrative wave to which the process of the invention can be applied will suggest themselves to those skilled in the art.

What is claimed is:

1. Apparatus for modifying the shape of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises filter means for partially smoothing said wave, thereby unavoidably displacing its zeros from said relative positions, and a zero-restoring network which comprises means for artificially interpolating in said partially smoothed wave a new set of zeros located at said certain relative positions, thereby to develop a compositive wave characterized by zero pairs, one pair for each original zero, and characterized, further, by a brief transient between the two members of each zero pair, and means for filtering said composite wave to remove said transients, thereby to generate a smooth wave having a single zero located between the two members of each zero pair.

2. Apparatus for modifying the shape of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises filter means for partially smoothing said wave, thereby unavoidably displacing its zeros from said relative positions, and a plurality of zero-restoring networks connected in tandem with said filter means, each of said networks comprising means for artificially interpolating in said partially smoothed wave a new set of zeros located at said certain relative positions, thereby to develop a composite wave characterized by zero pairs, one pair for each original zero, and characterized, further, by a brief transient between the two members of each zero pair, and means for filtering said composite wave to remove said transients, thereby to generate a smooth wave having a single zero located between the two members of each zero pair.

3. Apparatus as defined in claim 2 wherein the successive filtering means are proportioned to have successively narrower passbands.

4. Apparatus for modifying the shape of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises filter means for partially smoothing said wave, thereby unavoidably displacing its zeros from said relative positions, and a zero-restoring network which comprises means for rectifying said filtered wave, means for artificially interpolating in said rectified wave a new set of zeros located at said certain relative positions, thereby to produce a composite wave characterized by zero pairs, one pair for each original zero, and characterized, further, by a brief transient between the two members of each zero pair, and means for filtering said composite wave to remove said transients, thereby to generate a smooth wave having a single zero located between the two members of each zero pair.

5. Apparatus for modifying the shape of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises filter means for partially smoothing said wave, thereby unavoidably displacing its zeros from said relative positions, and a plurality of zero-restoring networks connected in tandem with said filter means, each of said networks comprising means for rectifying said filtered wave, means for artificially interpolating in said rectified wave a new set of zeros located at said certain relative positions, thereby to produce a composite wave characterized by zero pairs, one pair for each original zero, and characterized, further, by a brief transient between the two members of each zero pair, and means for filtering said composite wave to remove said transients, thereby to generate a smooth wave having a single zero located between the two members of each zero pair.

6. Apparatus as defined in claim 5 wherein the successive filtering means are proportioned to have successively narrower passbands.

7. Apparatus for deriving from a rectangular wave having a plurality of zero crossings that occur at irregular but significant instants on the time scale, each such zero crossing marking a sharp transition of said wave between a positive fixed amplitude portion and a negative fixed amplitude portion, a smooth, band-limited wave having zero crossings with the same relative dispositions on the time scale as those of the original wave which comprises a first low-pass filter, and a zero-restoring network which comprises a full wave rectifier, a modulator, and a second low-pass filter, connected together in tandem with said first filter in the order named.

8. Apparatus for deriving from a rectangular wave having a plurality of zero crossings that occur at irregular but significant instants on the time scale, each such zero crossing marking a sharp transition of said wave between a positive fixed amplitude portion and a negative fixed amplitude portion, a smooth, band-limited wave having zero crossings with the same relative dispositions on the time scale as those of the original wave which comprises a first low-pass filter proportioned to partially smooth said wave and unavoidably to shift its zeros, and a plurality of zero-restoring networks connected in tandem with said first filter, each of said networks comprising a full wave rectifier, a modulator, and a second low-pass filter, connected together in tandem with said first filter in the order named.

9. Apparatus as defined in claim 8 wherein the successive filters are proportioned to have successively narrower passbands.

10. In combination with a source of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion

products, apparatus for processing said wave to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises a first low-pass filter connected to said source, and a zero-restoring network connected to said filter which comprises a full wave rectifier, and a second low-pass filter, connected together in tandem in the order named, and a modulator interposed between said rectifier and said second filter, said modulator having an output point connected to said second filter and two input points of which one is connected to said rectifier, said irregular wave source being connected to the second input point of said modulator.

11. In combination with a source of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, apparatus for processing said wave to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises filter means connected to said source, for partially smoothing said wave, thereby unavoidably displacing its zeros from said relative positions, and a plurality of zero-restoring networks connected in tandem with said filter means, each of said networks comprising a full wave rectifier, and a second low-pass filter, connected together in tandem in the order named, and a modulator interposed between said rectifier and said second filter, said modulator having an output point connected to said second filter and two input points of which one is connected to said rectifier, said irregular wave source being connected to the second input point of said modulator.

12. Apparatus as defined in claim 11 wherein the successive filters are proportioned to have successively narrower passbands.

13. In combination with a source of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, apparatus for processing said wave to recover a smooth wave having zeros located at the same relative

positions on the time scale which comprises a first low-pass filter and a second low-pass filter, connected together in tandem to said source in the order named, and a modulator interposed between said first filter and said second filter, said modulator having an output point connected to said second filter and two input points of which one is supplied by the output of said first filter and the other is supplied by said irregular wave source.

14. Apparatus for modifying the shape of a wave characterized by an irregular sequence of information-bearing zeros that are located at certain relative positions on the time scale and by sharp corners representing distortion products, to recover a smooth wave having zeros located at the same relative positions on the time scale which comprises means for filtering said wave to partially smooth it, thereby unavoidably displacing its zeros from said relative positions, means for deriving a first train of pulses that are respectively coincident with the several zeros of said partially smoothed wave, means for deriving a second train of pulses that are respectively coincident with the several zeros of said irregular wave, means for combining said trains to form a train of pulse pairs, a utilization circuit, means for translating said partially smoothed wave to said utilization circuit, and means for inhibiting said translation under control of the first member of each of said pulse pairs and for restoring said translation under control of the second member of each of said pulse pairs.

15. Apparatus as defined in claim 14 wherein said inhibiting and restoring means comprises a scale-of-two counter.

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