

Dec. 24, 1957

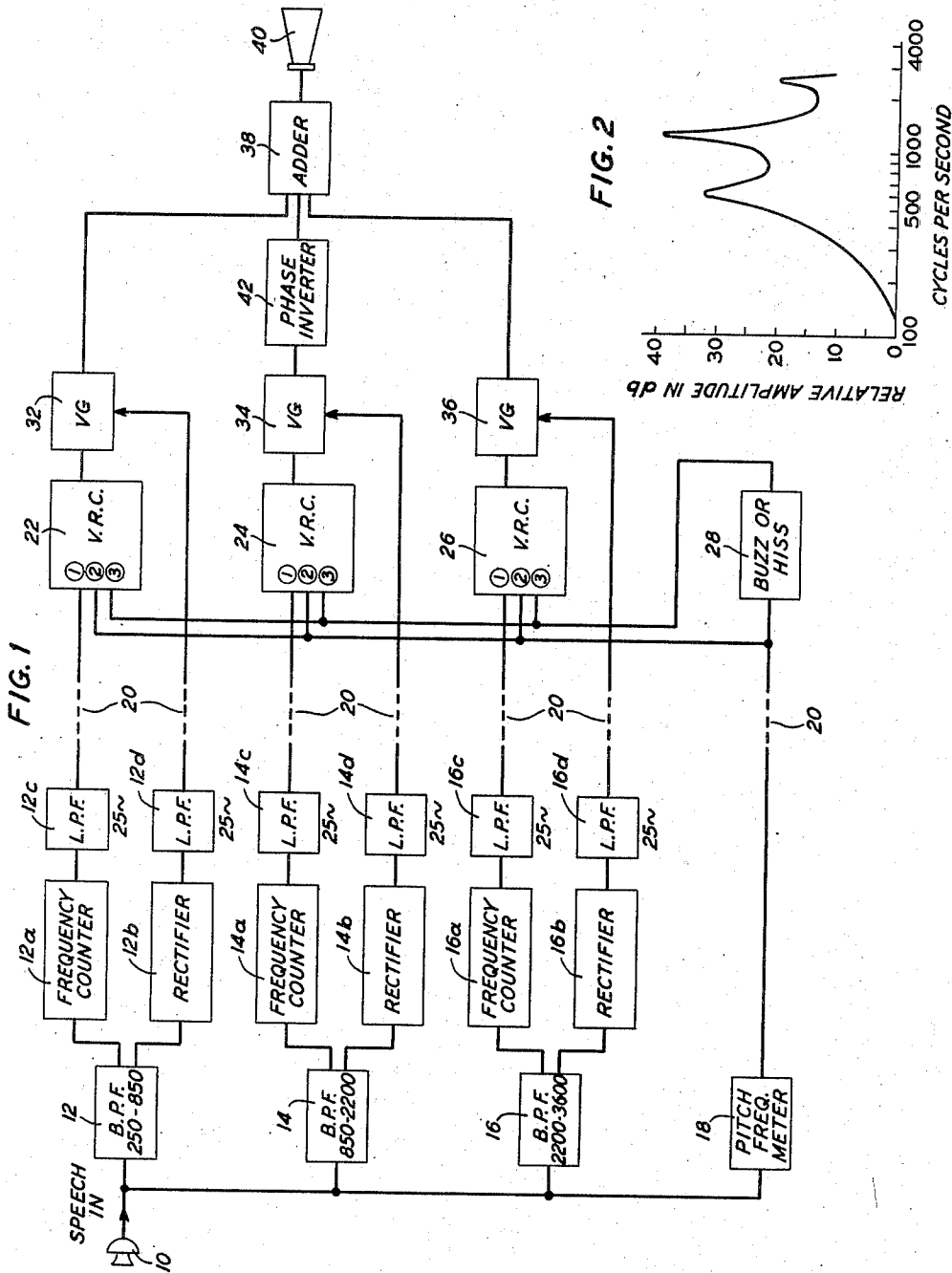
E. S. WEIBEL

2,817,707

SYNTHESIS OF COMPLEX WAVES

Filed May 7, 1954

3 Sheets-Sheet 1



INVENTOR
E. S. WEIBEL
BY *Harry C. Hart*
ATTORNEY

Dec. 24, 1957

E. S. WEIBEL

2,817,707

SYNTHESIS OF COMPLEX WAVES

Filed May 7, 1954

3 Sheets-Sheet 2

FIG. 3

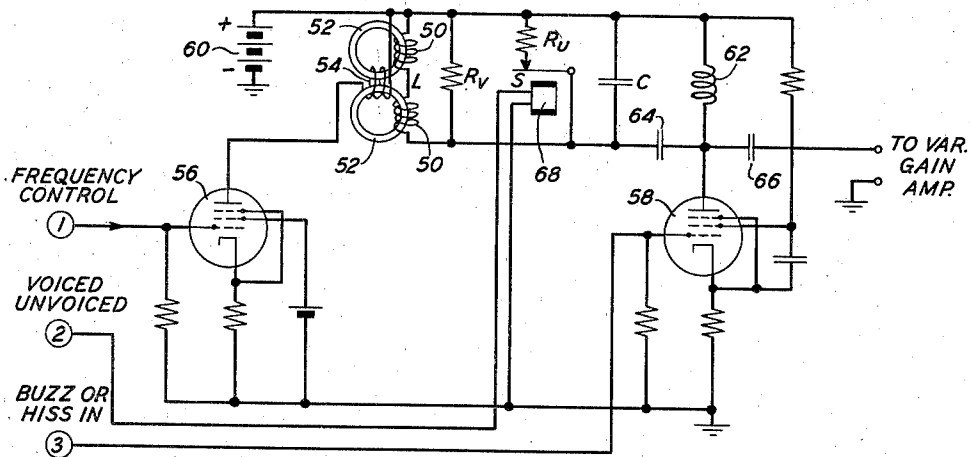
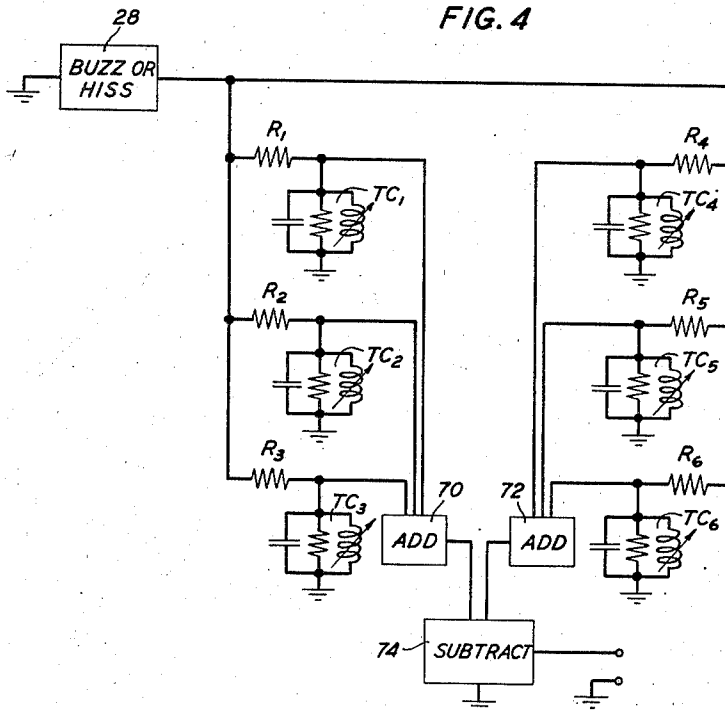


FIG. 4



INVENTOR
E. S. WEIBEL
BY
Harry C. Hart
ATTORNEY

Dec. 24, 1957

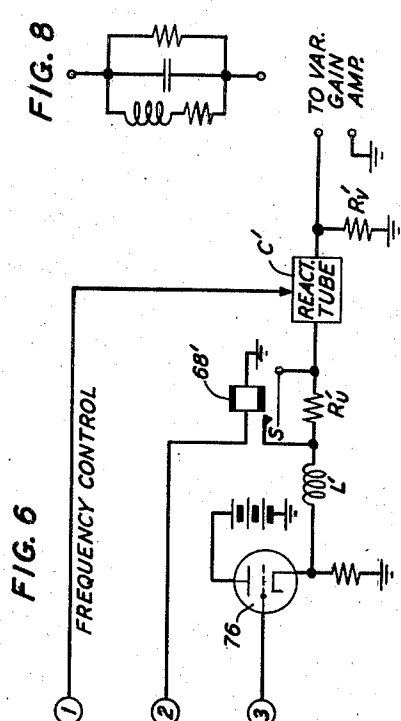
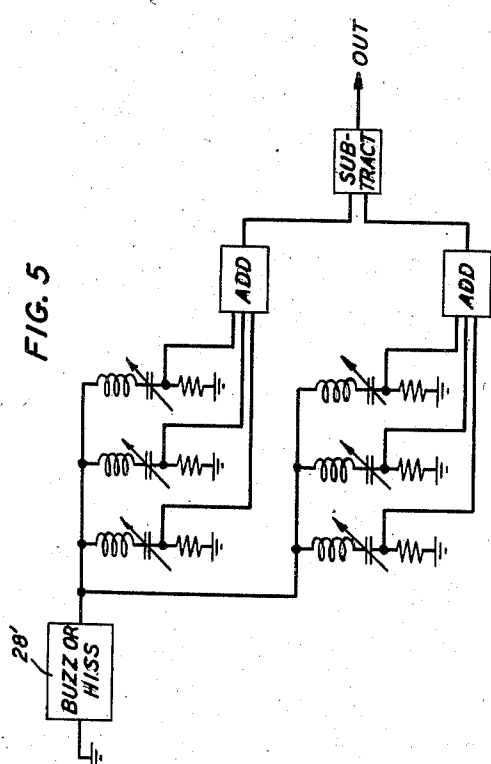
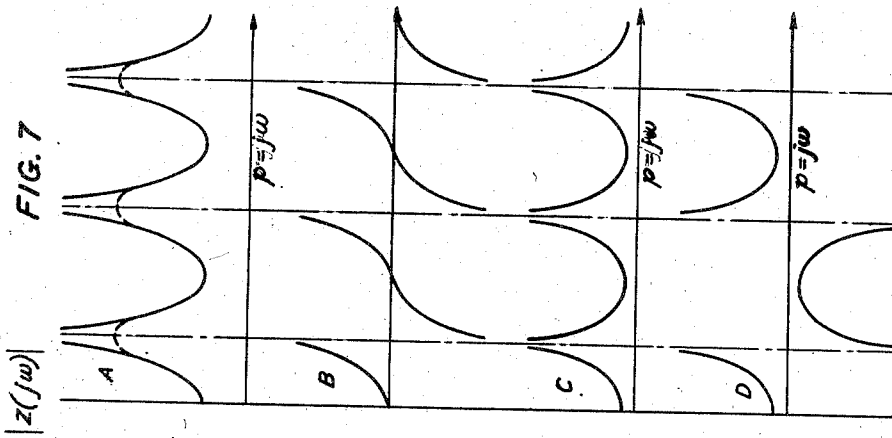
E. S. WEIBEL

2,817,707

SYNTHESIS OF COMPLEX WAVES

Filed May 7, 1954

3 Sheets-Sheet 3



INVENTOR
E. S. WEIBEL
BY
Harry C. Hart
ATTORNEY

1

2,817,707

SYNTHESIS OF COMPLEX WAVES

Erich S. Weibel, Summit, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 7, 1954, Serial No. 428,167

24 Claims. (Cl. 179—1)

This invention relates to the synthesis of complex waves.

A principal object of the invention is to improve the realism with which speech sounds may be artificially produced. A more general object is to construct an electric network which shall realize, as faithfully as possible, a preassigned transfer impedance function. A related object is to retain the significant features of such realized transfer impedance function in the presence of wide variations of its parameters.

One approach to the problem of narrow band speech transmission is represented by the vocoder. The first so-called "filter bank vocoder" is described in Dudley Patent 2,151,091. Experience with the filter bank vocoder led to an improvement known as the "resonance vocoder," various forms of which are described in Dudley Patent 2,243,527, in Vermeulen et al. Patent 2,458,227 and in Steinberg Patent 2,635,146. Briefly, such systems divide the voice frequency range into a small number, e. g., three, of comparatively wide bands, and derive a frequency control current and an amplitude control current for each band. These control currents, which occupy much narrower spectrum bands than the voice currents from which they are derived, are transmitted to a receiver station where they control the operation of artificial voice-synthesizing apparatus. A "hiss" source or a "buzz" source, as the case may be, in dependence on whether the sound being analyzed is unvoiced or voiced, is applied to a network whose function it is to simulate the vocal tract, and the elements of this network are altered by the control currents in a fashion to simulate the changes of configuration of the vocal tract which take place in the course of the articulation of speech sounds. To design a network which shall be suitable under all such conditions and which shall at the same time be readily alterable by the control currents poses a network design problem of substantial proportions.

One attempted solution to this problem is to provide a nonuniform electrical transmission line which is the dynamical counterpart at each point along its length of the acoustic transmission line comprised in the human vocal tract. Ideally, the transmission line is continuous; but as a practical matter it is composed of a finite number of lumped circuit element sections connected in tandem, the number being sufficiently large to provide a good approximation to the continuous line. Various parameters of this ladder network are representative of the corresponding parameters of the vocal tract, i. e., the location and height of the tongue hump, the magnitude of the lip opening, the disposition of the soft palate, etc.

This ladder network is described by H. K. Dunn in "The calculation of vowel resonances and an electrical vocal tract," published in the Journal of the Acoustical Society of America for November 1950, vol. 22, page 740, and also by L. O. Schott in "An electrical vocal system," published in the Bell Laboratories Record for December 1950, vol. 28, page 549. If control currents were available to represent these vocal tract parameters, they could be employed to vary the corresponding parameters of the

2

electrical ladder network and so cause it to duplicate electrically at all times the configuration of the vocal tract. However, the normal voice analyzer provides control currents which are representative not of the vocal tract configuration but of the formant frequencies of the voice. Inasmuch as every parameter of the electrical vocal tract plays a part in determining each of the formant frequencies of the artificially produced voice, all correlation between the control currents on the one hand and the variable parameters of the artificial tract on the other is lost in a maze of complexity.

Another solution to the network design problem is to provide a number of broadly tuned R—L—C circuits, one for each of the formant frequencies, and to drive them in parallel. This is the solution employed in the Steinberg and Vermeulen et al. patents referred to above. Experience with this system has shown, especially when it is attempted to vary the height on the transmission scale of any of the formant resonances, or its location on the frequency scale, or to alter its damping or sharpness of tuning, that serious difficulties are encountered, especially at frequencies lying between adjacent peaks of the transfer impedance function. At such frequencies the transfer impedance function of the electrical network has been found to depart widely from that of the vocal tract, being usually of much lower impedance, and always reaching the value zero at at least one frequency between adjacent resonance peaks.

In a search for the source of this difficulty, it has been recognized that the phase of the impedance of a parallel tuned or antiresonant circuit at frequencies above resonance, on its upper shoulder, leads the phase of the impedance at resonance by nearly 90 degrees, while its phase at frequencies on the lower shoulder lag its phase at resonance by the same amount. Consequently there exists a phase difference of nearly 180 degrees between the impedance at an upper shoulder frequency of the first formant resonance and the phase of the impedance at a lower shoulder frequency of the second formant resonance. These two frequencies are alike, or nearly alike. Consequently, partial or complete cancellation is to be expected. With series resonant circuits all phase relations are reversed so that the difficulty between formant peaks remains the same.

In seeking to resolve this difficulty, the transfer impedance function of the vocal tract to be simulated electrically has been reduced to mathematical form and expanded in a series of partial fractions. It turns out when this is done that every other term is preceded by a minus sign. In accordance with the present invention, the physical embodiment of such minus signs is furnished by the provision of an inversion of phase associated with alternate members of the group of tuned circuits of which the duplicating network is comprised. In the case of principal practical interest, the transfer impedance function of the vocal tract has three major peaks located at the frequencies of the first formant, the second formant and the third formant, respectively, and the simulating network comprises three resonant circuits which are individually tuned to these frequencies and driven in parallel from the same source. Each one is preceded by a high resistance to isolate it from the others and to make the driving source function as a current source. Each one is further provided with damping resistance in an amount to adjust its sharpness of tuning to correspond with that of the transfer impedance function peak which it represents. The present invention provides, in addition, a phase inverter associated with the second resonant circuit. An obvious alternative is to associate phase inverters with the first resonant circuit and the third, leaving the phase of the second resonant circuit uninverted.

In a second form of the invention each resonant circuit with its driving source is the dual counterpart of the corresponding resonant circuit and driving source in the first form. That is to say, series tuned circuits are employed and driven from low impedance sources. As in the first form, the phase of the output of the second tuned circuit is inverted with respect to the phases of the outputs of the first and third.

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

Fig. 1 is a block schematic diagram showing a vocoder transmission system including conventional voice analyzer apparatus and synthesizer apparatus, modified in accordance with the invention;

Fig. 2 represents on the frequency scale the transfer impedance function of a typical human vocal tract pronouncing a vowel sound;

Fig. 3 is a schematic circuit diagram showing circuit details of one of the variable resonant circuits of Fig. 1;

Fig. 4 is a schematic circuit diagram showing a generalization of the synthesizer apparatus of Fig. 1 and illustrating the principles of its operation;

Fig. 5 is a schematic circuit diagram showing apparatus which is the dual counterpart of the apparatus of Fig. 4;

Fig. 6 is a schematic circuit diagram showing details of the apparatus of Fig. 5;

Fig. 7 shows the absolute value of an idealized transfer impedance function, and graphs of some functions referred to in the exposition; and

Fig. 8 shows a tunable circuit whose structure is arrived at by analysis of the characteristics of Fig. 7.

Referring now to the drawings, the left-hand portion of Fig. 1 shows conventional apparatus for analyzing a voice and generating control signals. Speech waves originating, for example, at a microphone 10 are delivered in parallel to three band pass filters, 12, 14, 16 whose pass bands, indicated in the figure, correspond respectively to the normal locations on the frequency scale of the first, second and third formants of the voice. Thus, the pass band of the first filter 12 extends from 250 C. P. S. to 850 C. P. S., that of the second filter 14 from 850 C. P. S. to 2200 C. P. S., and that of the third filter 16 from 2200 C. P. S. to 3600 C. P. S. These bands embrace the resonance peaks of the first, the second, and the third formants of the human voice as well as their shifts on the frequency scale, which take place in the course of normal speech. These formants are illustrated, for a typical vowel sound, in Fig. 2, which shows the formant peaks at 600 C. P. S., 1200 C. P. S. and 2500 C. P. S., respectively.

The voice energy which passes through each of these filters, e. g., the filter 12, is applied simultaneously to a frequency measuring device 12a which delivers a formant frequency control signal, and to an amplitude measuring device 12b which delivers a formant amplitude control signal. Each of these control signals passes through a low pass filter 12c, 12d, which restricts the band which it occupies to about 25 C. P. S. The frequency measuring device 12a may be an axis crossing counter and the amplitude measuring device 12b may be a simple rectifier. Similar devices, similarly identified, are associated with the filters 14, 16.

In addition, the speech energy is applied to a pitch detector 18 which delivers a control signal representative of the fundamental frequency of the voice. The latter may be as shown in Riesz Patent 2,522,539, Fig. 3, or otherwise, as desired.

The pitch control signal and the two control signals for each formant are transmitted in any desired fashion over an intervening medium, symbolized on the drawing merely by broken lines, to a receiver or synthesizer station. Here the pitch control signal operates and con-

trols the frequency of a buzz source and, when it falls below a preassigned low amplitude threshold, indicating the absence of a voiced sound at the transmitter, turns off the buzz source and permits a hiss source to be turned on in its stead. The buzz source and its controlled tuning, the hiss source, and the mechanism which selects as between them, may be as shown in Riesz Patent 2,522,539, Fig. 3. They are together symbolized by the block 28.

Three variable resonant circuits 22, 24, 26 are provided, one of which corresponds to the first voice formant, one to the second and one to the third. Each of them is provided with three input points labeled 1, 2 and 3, respectively, on the drawing. The first formant frequency control signal, from the filter 12c, is applied to the first input point of the first variable resonant circuit 22. The second formant frequency control signal, from the filter 14c, is applied to the first input point of the second variable resonant circuit 24, and the third formant frequency control signal, from the filter 16c, is applied to the first input point of the third variable resonant circuit 26. The pitch control signal, from the frequency meter 18, is applied in parallel to the No. 2 input points of all three of the variable resonant circuits 22, 24, 26 while the output of the buzz source or the hiss source 28, as the case may be, is applied in parallel to the No. 3 input points of all three of the variable resonant circuits 22, 24, 26.

In tandem with the output terminals of the several variable resonant circuits 22, 24, 26 there are connected elements 32, 34, 36 which introduce controllable amounts of gain or attenuation. These may be simple variable gain amplifiers and the amplitude control signals of the several formants from the filters 12d, 14d, 16d are applied to the gain control terminals of these amplifiers.

The outputs of the several variable gain amplifiers are additively combined as by application to an adder 38 whose output in turn feeds a sound reproducer 40. In accordance with the present invention, a phase inversion is introduced in series between the buzz or hiss source 28 and the adder 38 in the case of alternate ones of the group of variable resonant circuits. Inasmuch as for voice reproduction purposes, three such variable resonant circuits normally suffice, the most economical fashion in which such alternate phase inversions may be introduced is to provide a phase inverter 42 in the second path only. It is shown as following the variable gain amplifier although obviously it could equally well be inserted ahead of the variable gain amplifier 34 or ahead of the variable resonant circuit 24 in series with its No. 3 input point.

The details of a circuit suitable for any one of the variable resonant circuits 22, 24, 26 of Fig. 1 are illustrated in Fig. 3. The heart of this figure comprises a parallel arrangement of a fixed condenser C, a variable inductance element L and a fixed damping resistor R_v (voiced), and provision for supplying it with energy from a current source. A second fixed resistor R_u (unvoiced) in series with relay contacts S is shunted across the first resistor R_v for a purpose to be explained.

With a parallel tuned or antiresonant circuit of this type, the amplitude of the resonance curve, i. e., the magnitude of its impedance at resonance is given by

$$Z_r = \frac{1}{2\pi C \Delta f} \quad (1)$$

where Δf is the width of the resonance curve between two frequencies located on either side of the resonance frequency at which the magnitude of the impedance is reduced by three decibels from its magnitude at resonance. Furthermore, this width Δf is given by

$$\Delta f = \frac{1}{2\pi RC} \quad (2)$$

From Equations 1 and 2 it follows that both the magnitude of the circuit impedance at resonance as defined by Equation 1 and its band width as defined by Equation 2 are independent of the inductance L . Hence, provided that tuning be accomplished solely by changing the magnitude of the inductance L , each resonance of Fig. 2 may be shifted on the frequency scale without altering either its height or its width. Therefore, in accordance with another aspect of the invention, tuning of the resonant circuit L, C, R_v , is preferably accomplished, with retention of the character of the transfer impedance function to be duplicated, by varying the magnitude of the inductance L while holding the magnitudes of the condenser C and of the resistor R_v fixed. To this end the inductance L may appropriately comprise a pair of windings 50 on magnetizable cores 52 which also bear a control winding 54 and the frequency control signal applied to the No. 1 input point may be raised in level and caused to flow through this control winding 54 as by the interposition of an amplifier. A pentode vacuum tube 56 serves both these purposes while at the same time introducing a high resistance in series with the control winding 54.

The inductance of the signal windings 50 of commercially available saturable reactors is substantially inversely proportional to the square of the magnitude of the control current flowing through the control winding 54. Because the frequency of resonance of the $R-L-C$ circuit is substantially in inverse proportion to the square of the magnitude of its inductance element L , the condenser C being fixed, it follows that the resonant frequency of the tuned circuit is proportional to the first power of the frequency control signal, a relation which makes for convenience in operation.

In accordance with a feature of the invention, this tuned circuit is preferably fed from the buzz or hiss source 28 applied to its No. 3 input point by way of a high impedance which is effectively realized by a pentode vacuum tube 58 of known construction, e. g., a tube designated by the standard code 6AU6. This tube is powered from the positive terminal of an operating voltage supply 60 through a choke coil 62 and its anode is connected by way of a blocking condenser 64 to one terminal of the antiresonant circuit. With this arrangement the tuned circuit is supplied with current whose magnitude is independent of frequency, wherefore the voltage derived across the circuit is proportional at each frequency to the circuit impedance. This output voltage may conveniently be applied by way of a coupling condenser 66 to the variable gain amplifier 32, 34, or 36.

The pitch control signal derived at the transmitter station, in addition to tuning the buzz source 28 and switching as between the buzz source and the hiss source, is also employed to vary the damping of the tuned circuit $R-C-L$. To this end, it is applied at input terminal No. 2 of the variable resonant circuit of Fig. 3 where, when it exceeds a preassigned threshold indicating the presence of strong voicing in the sound being analyzed, it actuates a relay 68 which draws its armature away from the contact thus opening the switch S in series with the resistor R_u . When the pitch control current falls below this preassigned threshold indicating the presence of an unvoiced sound, the relay spring closes its back contact and so connects the resistor R_u in shunt with the resistor R_v , thus increasing the damping of the circuit to a higher level as is appropriate for the production of unvoiced sounds.

Each of the variable resonant circuits 22, 24, 26, may be constructed as described above for any one of them. The various circuit constants are then adjusted in relation to the characteristics of the several formant resonant peaks, e. g., those of Fig. 2. Thus, for example, Fig. 2 represents, specifically, the vowel sound a , as in the English word "appeal." Suitable circuit constant values, together with the formant frequencies and band

widths to which they give rise, are given in the following table:

V. R. C. 22 (First formant)	V. R. C. 24 (Second formant)	V. R. C. 26 (Third formant)
$L=1.7$ henries $C=0.04$ μ fd. $R_v=40,000$ ohms $f_1=600$ C. P. S. $\Delta f=96$ C. P. S.	$L=0.57$ henries $C=0.03$ μ fd. $R_v=40,000$ ohms $f_2=1,200$ C. P. S. $\Delta f=132$ C. P. S.	$L=0.16$ henries $C=0.025$ μ fd. $R_v=40,000$ ohms $f_3=2,500$ C. P. S. $\Delta f=164$ C. P. S.

When, to these values, there are added various gains, as provided by the amplifiers 32, 34, 36, having the relative magnitudes

$$G_1=12 \text{ db}, G_2=19 \text{ db}, G_3=0 \text{ db}$$

the curve of Fig. 2 is duplicated with substantial exactness.

The invention may readily be generalized to include the duplication of a transfer impedance function having many more peaks than three, e. g., one having six peaks. Appropriate apparatus for this is shown in simplified schematic form in Fig. 4. Here six parallel resonant circuits, TC_1 to TC_6 , inclusive, are provided to correspond with the transfer impedance function peak which it is their object to represent. Each comprises an inductor, a condenser, and a resistor. They are all fed in parallel from a buzz or hiss source 28, as the case may be, and through high impedances represented by resistors R_1 to R_6 , inclusive. The outputs of the first, the third, and the fifth tuned circuits TC_1, TC_3, TC_5 are combined by a first adder 70 and the outputs of the second, the fourth and the sixth tuned circuits TC_2, TC_4, TC_6 are combined in a second adder 72. The outputs of these two adders 70, 72 are then combined in a subtractor 74 whose output may be supplied to a reproducer. This arrangement of two adders and one subtractor connected as shown evidently introduces a phase inversion of 180 degrees as between the output of each of the tuned circuits and that of the next higher numbered tuned circuit.

Fig. 5 shows the dual counterpart of Fig. 4. The tuned circuits are now series resonant circuits L', R_v', C' , and are fed from a buzz or a hiss source 28' of low impedance. Thus, referring to Fig. 6, each such series tuned circuit is fed from a cathode follower 76 which, as is well known, constitutes a low impedance source. A resistor R_v' forms a fixed part of this resonant circuit and its magnitude is adjusted to introduce an amount of damping equal to that of the formant peak of the transfer impedance function to which it corresponds. In addition, a second resistor R_u' is included in series and shunted by contacts which may be actuated by a relay 68' as in Fig. 3 to place it in the circuit for an unvoiced sound and to remove it therefrom for a voiced sound.

To vary the tuning of the circuit in this dual form, it is preferable to hold the inductance element L' fixed and to vary the capacitance element C' . This may be accomplished in known fashion by employment for such capacitance element of a conventional reactance tube circuit and by application of the pitch control signal to its control terminal. A variable gain amplifier or other device for adjusting the amplitude of the output of the circuit is preferably connected in series as before and controlled as in the case of Fig. 1 by the amplitude control signal.

Although the invention has been illustrated in two alternative forms as applied to a vocoder transmission system, it will be evident that it is equally applicable to any other system in which it is required to duplicate the transfer impedance of any variable nonuniform transmission line, to shift it bodily on the frequency scale, to vary within limits the spacing on the frequency scale between its peaks, and to vary within limits the relative

magnitudes of its major peaks while still retaining its general character.

Analytical considerations

It is of interest to consider the analytical foundations on which the invention is based.

The transfer impedance function of a continuous linear transmission system such as the vocal tract, when regarded as a function of the complex frequency p , belongs to a class of functions which may be expressed, through a partial fraction expansion, by the series

$$Z(p) = Z(o) + \sum \left(\frac{a_n}{p - p_n} + \frac{a_n}{p - \bar{p}_n} \right) \quad (3)$$

where each a_n is the residue at the pole p_n . This is a consequence of the Mittag-Leffler theorem (Whittaker and Watson: *Modern Analysis*; Cambridge University Press, 1927, page 134).

These poles and their residues occur in conjugate complex pairs, namely

$$\begin{aligned} p_n &= j\omega - \sigma, a_n = A_n + jB_n, \\ p_{-n} &= -j\omega - \sigma, a_{-n} = A_n - jB_n \end{aligned} \quad (4)$$

When the terms of (3) for each such conjugate pair of poles are combined, there results immediately

$$Z(p) = Z(o) + \sum 2A_n \left[\frac{p + \sigma_n + \omega_n \frac{B_n}{A_n}}{(p + \sigma_n)^2 + \omega_n^2} + \frac{\sigma_n + \omega_n \frac{B_n}{A_n}}{\sigma_n^2 + \omega_n^2} \right] \quad (5)$$

and, after making the substitutions

$$\left. \begin{aligned} L &= \frac{2A}{\omega^2 \left(1 + \frac{B^2}{A^2} \right)}, r = \frac{\sigma + \omega \frac{B}{A}}{2A} \omega^2 \left(1 + \frac{B^2}{A^2} \right) \\ C &= \frac{1}{2A}, g = \frac{\sigma - \omega \frac{B}{A}}{2A} \end{aligned} \right\} \quad (6)$$

$$Z(p) = \frac{1}{C} \frac{p + \frac{r}{L}}{p^2 + \left(\frac{r}{L} + \frac{g}{C} \right) p + \frac{1}{LC} + \frac{rg}{LC}} \quad (7)$$

It is well known that this expression represents the impedance of an electric circuit having the configuration shown in Fig. 8.

Within the range of practical interest, it turns out that each of the circuit elements of Fig. 8 is physically realizable. It turns out, further, that the required magnitude of the resistor r is so small that it may be neglected entirely, in which case Equation 7 reduces to

$$Z(p) = \frac{1}{C} \frac{p}{p^2 + \frac{g}{C} p + \frac{1}{LC}} \quad (8)$$

To derive from the circuit of Fig. 8 a voltage which is substantially proportional to the impedance (7) or (8), it is of course important to drive the circuit from a high impedance source which in effect supplies it with a current which is independent of frequency.

With this restriction Equations 1 and 2 follow from Equation 8 and with them the result that inductance tuning of any one of the variable resonant circuits of Figs. 1 and 3 shifts the corresponding resonance of Fig. 2 on the frequency scale without altering either its width or its amplitude, and without in any way affecting the other resonances.

The invention is based in part upon the discovery that the real parts of the residues A_n of Equation 5 are of successively opposite algebraic signs at the successive poles p_n . To establish this fact, consider first the situation in which the losses and dissipation of the vocal tract are nonexistent or are disregarded. The complex frequency p now reduces to its imaginary part $j\omega$ and the poles of

the transfer impedance function of Fig. 2 appear on the ω axis. Curve A of Fig. 7 shows a plot of the transfer impedance function of Fig. 2 for this ideal case with its idiosyncrasies omitted and its general character retained, including the fact that its absolute value is plotted; i. e., the algebraic signs of its branches are concealed.

When the function itself is plotted with the restriction to absolute value removed, it must have one of three forms, shown in curves B, C, and D, respectively, of Fig. 7. Curve B is characterized by zeros alternating with simple poles. Curve C has no zeros but has instead second order poles. Curve D has simple poles and no zeros.

Now the possibility of representation by curve B is excluded by the known fact that the transfer impedance, Fig. 2, has no zeros. The possibility of representation by curve C is excluded by a theorem which establishes that any real continuous transmitting structure which has poles has only simple poles. (See E. A. Guillemin: "A summary of modern methods of network synthesis," *Advances in Electronics*, vol. III, page 275; Academic Press, Inc., New York, 1951.) Thus, the only remaining possibility is curve D which thus represents the transfer impedance function in question.

From an examination of curve D, it is obvious that, whatever the sign of the residue at the first pole may be, the residue at the second pole is of opposite sign to that at the first, the residue at the third pole is of the same sign as that at the first, and so on, the residues at the successive poles alternating regularly in sign. Hence, the individual circuits which represent the individual formant resonances, and whose additive combination is to represent the entire transfer impedance function, must be oppositely phased, each with respect to the ones of next lower and next higher order.

Consider next what effect the introduction of finite losses in the vocal tract may have on the consequences of the preceding development. The poles of $Z(p)$ now disappear from the real frequency axis and are replaced by poles in the left half of the complex frequency plane. The absolute value of the transfer impedance is now represented by the broken curve of Fig. 7; i. e., it has maxima instead of poles and the real residues A_n are replaced by complex residues, $A_n + jB_n$. For small losses, the change in A_n and the magnitude of B_n are both small; i. e., they are insufficient to change the alternation of sign which has been shown to occur in the lossless case. Hence in the real situation as in the ideal situation, the individual electric circuits which may represent the individual resonances and whose additive combination is to represent the entire transfer impedance function, must be oppositely phased, each with respect to the ones of next lower and next higher order.

What is claimed is:

1. Apparatus having a transfer impedance from a source to a load, which impedance has the same functional form as that of a continuous nonuniform transmission structure of distributed parameters, and is characterized by at least two resonance peaks at different frequencies and by a trough between said peaks of amplitude greater than zero and substantially less than either peak amplitude, which comprises a first circuit resonant at the frequency of said first peak, a second circuit resonant at the frequency of said second peak, means for supplying oscillatory energy of a common source to said circuits in parallel, means for deriving oscillatory energy from said circuits and for supplying it to a common load, and a phase-inverting device interposed in series arrangement with one of said circuits between said source and said load.

2. Apparatus having a transfer impedance from a source to a load, which impedance has the same functional form as that of a continuous nonuniform transmission structure of distributed parameters and is characterized by a plurality of resonance peaks at different fre-

quencies and by a trough, between each pair of adjacent peaks, of amplitude greater than zero and substantially less than said adjacent peak amplitudes, which comprises a circuit resonant at the frequency of each of said peaks, means for supplying oscillatory energy of a common source to all of said circuits in parallel, means for deriving oscillatory energy from all of said circuits and for supplying it to a common load, and a phase-inverting device interposed in series arrangement with each alternate one of said circuits between said source and said load.

3. Apparatus as defined in claim 1 wherein each resonant circuit comprises an inductor, a capacitive element, and a resistor.

4. Apparatus as defined in claim 3 wherein the resistor of each resonant circuit is proportioned in relation to the capacitive element in a fashion to endow the resonant circuit with a band width equal to that of the transfer impedance characteristic peak at whose peak frequency it is resonant.

5. Apparatus as defined in claim 1 wherein each resonant circuit comprises an inductor, a capacitive element and a resistor, all connected in parallel.

6. In combination with apparatus as defined in claim 5, an impedance element connected in series between the energy source and each resonant circuit, the impedance of said element being substantially greater than the resonant impedance of said circuit.

7. Apparatus as defined in claim 6 wherein said source supplies said circuits with currents whose magnitudes are substantially independent of frequency and wherein the resulting voltage developed across each of said circuits is supplied to the common load.

8. Apparatus as defined in claim 1 wherein each resonant circuit comprises an inductor, a capacitive element and a resistor, all connected in series.

9. Apparatus as defined in claim 8 wherein the impedance of the energy source is substantially lower than the resistance of said circuit.

10. Apparatus as defined in claim 8 wherein said source supplies said circuits with voltages whose magnitudes are substantially independent of frequency and wherein a voltage proportional to the resulting current flowing through each of said circuits is supplied to the common load.

11. Apparatus for the artificial production of voice sounds which comprises a consecutively numbered group of tunable R—L—C circuits, each of which has a natural frequency substantially equal to a similarly numbered one of a series of voice formant frequencies, means for applying the energy of an oscillation source to all the members of said circuit group in parallel, means for deriving a first oscillatory output from all the odd-numbered members of said circuit group in one phase, means for deriving a second oscillatory output from all the even-numbered members of said circuit group in opposite phase, and means for additively combining said first and second outputs.

12. Apparatus for the artificial production of voice sounds which comprises a consecutively numbered group of tunable R—L—C circuits, each of which has a natural frequency substantially equal to a similarly numbered one of a series of voice formant frequencies, means for applying the energy of an oscillation source to all the members of said circuit group in parallel, means for deriving oscillatory energy from all the members of said circuit

group and for applying it to a common load, and a phase-inverting device interposed in series arrangement with each alternate member of said circuit group between said source and said load.

13. Apparatus as defined in claim 12 wherein the resistor of each R—L—C circuit is proportioned in relation to the capacitive element in a fashion to endow the R—L—C circuit with a band width equal to that of a selected one of the voice formant resonances.

14. Apparatus as defined in claim 12 wherein each R—L—C circuit comprises an inductor, a capacitive element and a resistor, all connected in parallel.

15. In combination with apparatus as defined in claim 14, an impedance element connected in series between the energy source and each R—L—C circuit, the impedance of said element being substantially greater than the resonant impedance of said R—L—C circuit.

16. In combination with apparatus as defined in claim 15, means for varying the magnitude of the inductance element of each R—L—C circuit to alter its resonant frequency.

17. In combination with apparatus as defined in claim 16, means for selectively shunting the resistor of each R—L—C circuit with an auxiliary resistor thereby to increase the damping of said circuit.

18. Apparatus as defined in claim 12 wherein each R—L—C circuit comprises an inductor, a capacitive element and a resistor, all connected in series.

19. Apparatus as defined in claim 18 wherein the impedance of the energy source is substantially lower than the resistance of said R—L—C circuit.

20. In combination with apparatus as defined in claim 19, means for varying the magnitude of the capacitance element of each R—L—C circuit to alter its resonant frequency.

21. In combination with apparatus as defined in claim 20, means for selectively inserting an auxiliary resistor in series with each R—L—C circuit thereby to increase the damping of said circuit.

22. Apparatus for the artificial production of voice sounds which comprises a consecutively numbered group of tunable resonant circuits, each of which has a resonant frequency corresponding to that of a similarly numbered one of a series of voice formant frequencies, an oscillation source, means for applying the energy of said oscillation source to all of said resonant circuits in parallel, means for combining the oscillatory outputs of odd-numbered ones of said resonant circuits to provide a first combined output, means for combining the oscillatory outputs of even-numbered ones of said resonant circuits to provide a second combined output, and means for adding in opposite phase said first and second combined outputs.

23. Apparatus as set forth in claim 22 wherein each of said resonant circuits comprises elements connected in parallel.

24. Apparatus as set forth in claim 22 wherein each of said resonant circuits comprises elements connected in series.

References Cited in the file of this patent

UNITED STATES PATENTS

2,340,364	Bedford	Feb. 1, 1944
2,458,227	Vermeulen et al.	Jan. 4, 1949
2,512,889	Dreyfus	June 27, 1950