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2,429,236

ANALYSIS AND REPRESENTATION OF COMPLEX WAVES

Filed April 5, 1945

2 Sheets-Sheet 1

FIG. 1

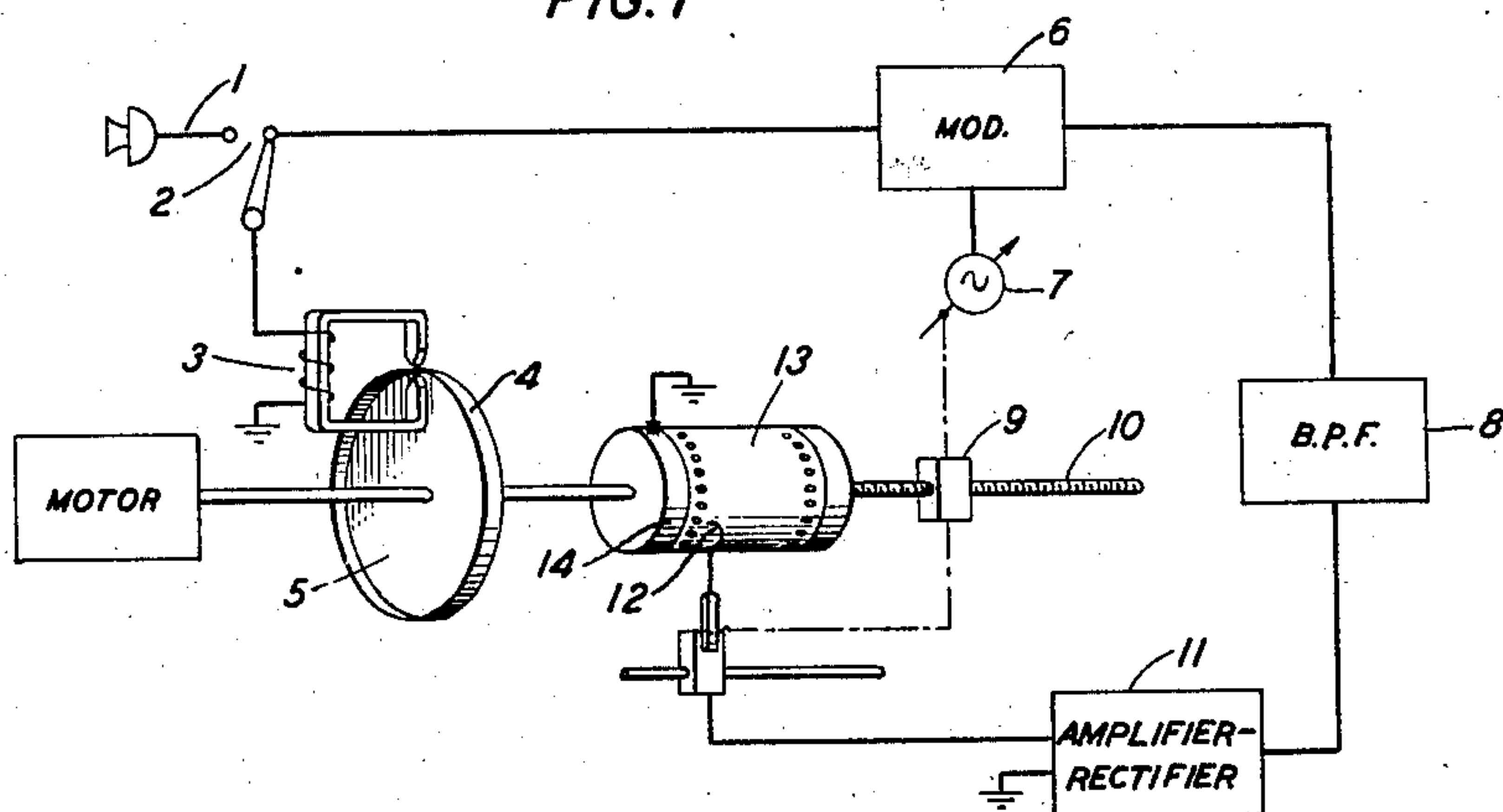
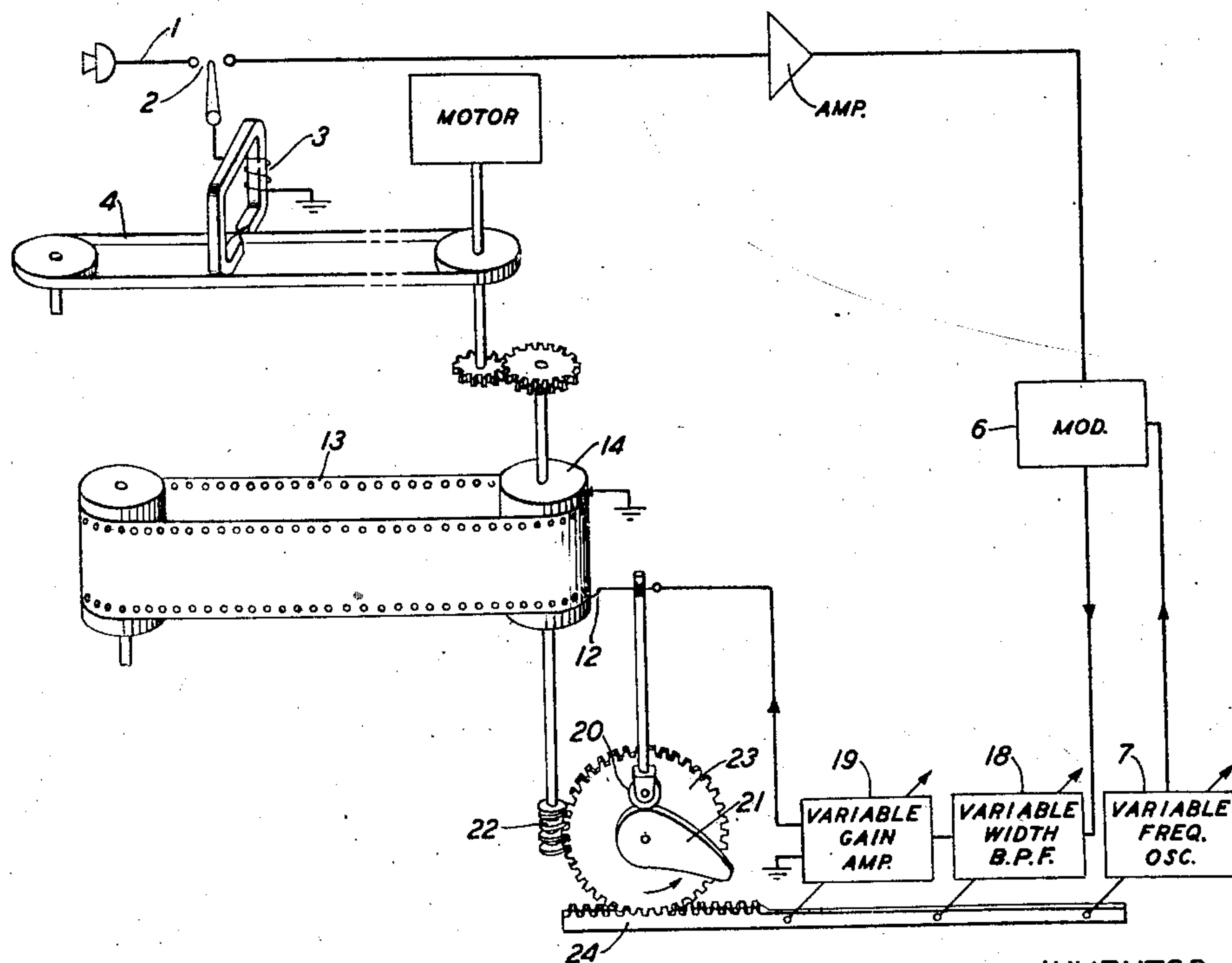


FIG. 2



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2 Sheets-Sheet 2

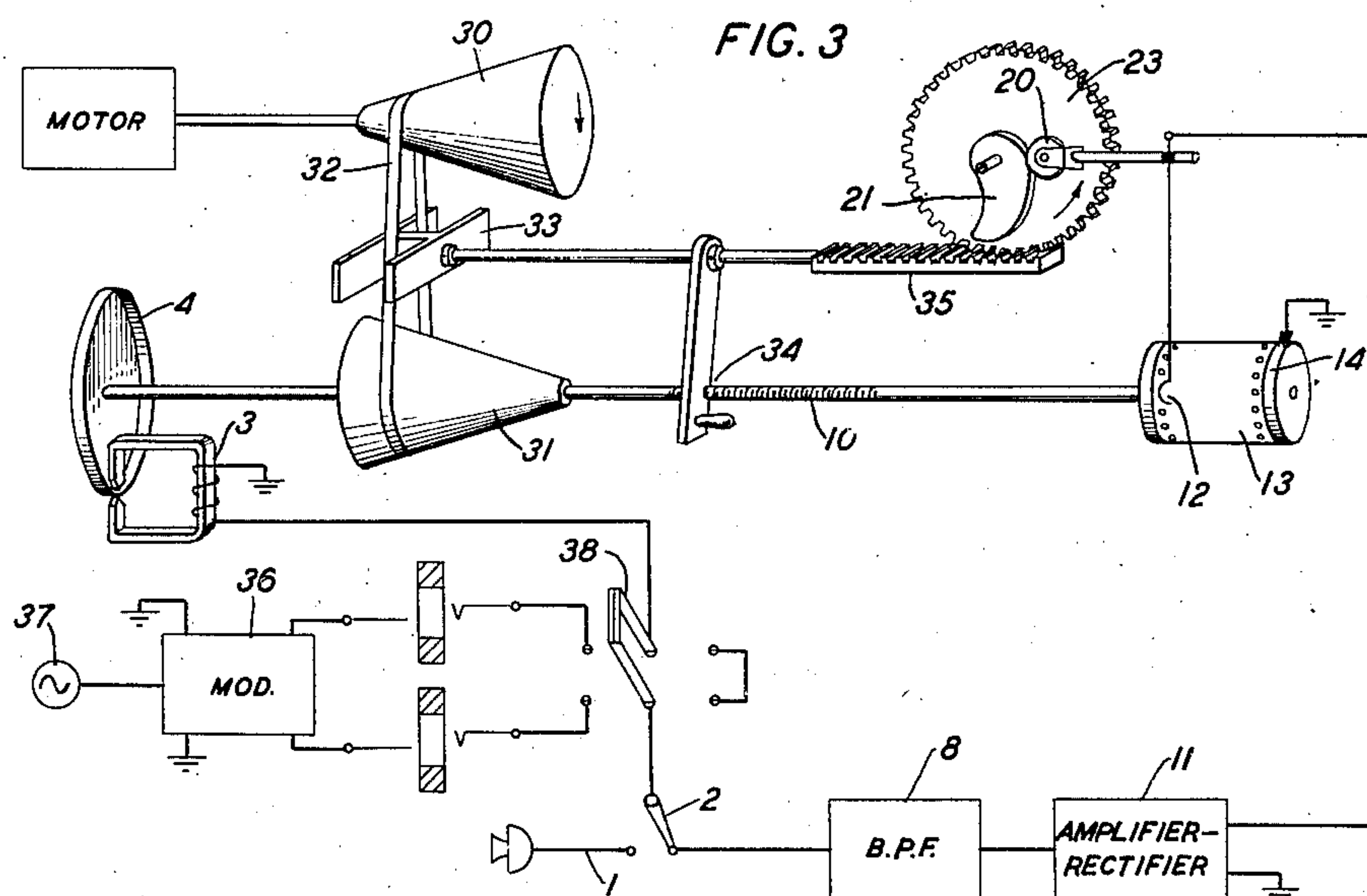


FIG. 4

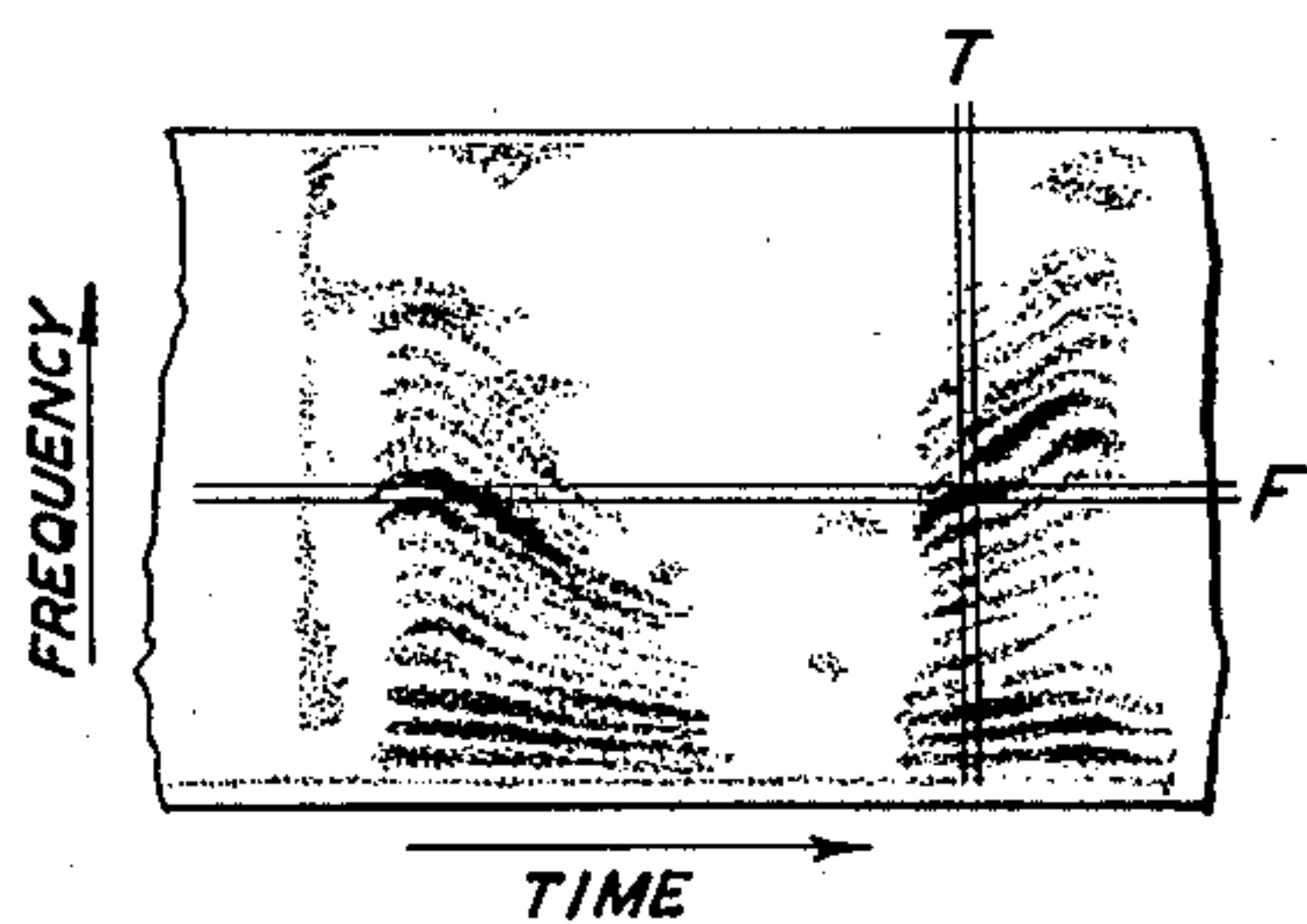
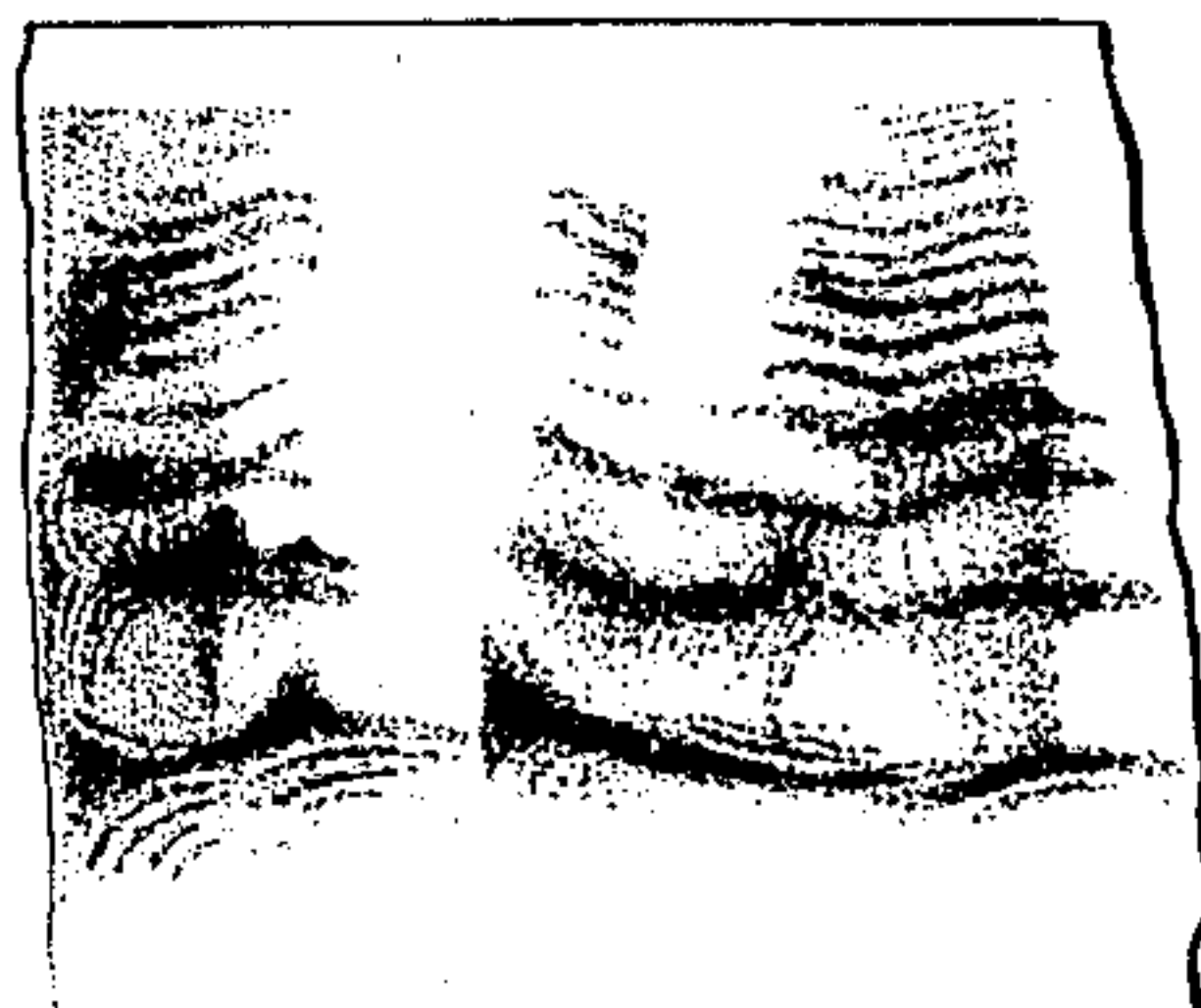


FIG. 5



FIG. 6



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ANALYSIS AND REPRESENTATION OF
COMPLEX WAVES

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Application April 5, 1945, Serial No. 586,769

19 Claims. (Cl. 179—1)

1

This invention relates to the analysis and visual representation of complex waves, and more especially but not exclusively to the frequency analysis and visual representation of sound waves of varying frequency composition such as music and speech bearing waves.

One of the objects of the invention is to produce an improved visual record of complex waves in a form such as to show directly how the wave power is distributed across the frequency range at any time and how the wave power in any part of the frequency range varies with time.

A further object is to produce an improved visual record of complex waves in which the dimensions, or dimensional coordinates, of the visual record have the sense of coordinate axes, or scales, representing frequency and time, respectively.

Another object of the invention is to picture sound waves as the ear hears them, that is, to simulate the characteristics of the human ear in the translation of sound waves into a visual representation.

Still another object of the invention is to provide improved methods and means for translating speech bearing waves into a visual representation that is susceptible of being read.

A further object is to improve and simplify apparatus and methods for analyzing and graphically recording the varying composition of complex waves.

A visual representation of complex waves in accordance with the present invention may take the general form disclosed in my copending application Serial No. 438,878, filed April 14, 1942 (U. S. Patent No. 2,403,997, July 16, 1946), in which the width of the record surface has the sense of a frequency axis and the length has the sense of a time axis, whereby each elemental area is respective to a particular frequency band and to a particular time interval, and in which the visual record formed on the surface serves to indicate for each such elemental area the average wave power, or amount of wave energy, that appeared in the frequency band respective to the area during the time interval respective to the area. The visual record may take on the appearance of a half-tone picture in which the density or darkness of the record in any elemental area is a measure of the wave energy to be indicated. Other visually distinguishable attributes of the visual record may be used alternatively to indicate the wave energy or intensity factor. I have successfully used different colors, for example, to represent different values of intensity, for the pur-

2

pose of providing a visual interpretation of, and accompaniment for, music; and another example, adapted primarily for accurate analytical work, is disclosed in my copending application Serial No. 569,557, filed December 23, 1944.

The intensity that is represented at any point in a "spectrogram" of the kind described is the effective intensity or envelope amplitude of the wave component or components appearing in a predetermined frequency band, or in other words what is represented is the wave power content or varying average energy appearing in the predetermined band. This is not to be confused with the varying instantaneous amplitude of the wave components. The instantaneous amplitude of a single-frequency component varies sinusoidally at a rate proportional to the frequency of the component whereas the effective intensity, or envelope amplitude, or power content, varies as the strength or loudness of the component varies. Lacking a record of the variations in instantaneous amplitude the spectrogram requires highly specialized reproducing equipment for translating it back into sound waves should such be desired.

The reproducing equipment itself supplies the various tones, as disclosed in my copending application Serial No. 586,768, filed April 5, 1945, and the record of the variations in effective intensity that is contained in the spectrogram is utilized to control the relative strengths of the several tones.

The frequency analyzing and recording apparatus, or "sound spectrograph," that is employed to form a spectrogram of complex waves, may be designed to afford one degree of frequency resolution or another. That is, it may be designed to discriminate between wave components that differ only slightly in frequency, and to show these components distinctly and separately in the spectrogram, or it may be designed to have a much lesser degree of discrimination and to produce a spectrogram which, while it may have other virtues, is relatively lacking in frequency definition. The degree of frequency resolution is largely dependent on the selectivity or band width of the means employed for resolving the complex wave into its various components.

A feature of the present invention is a sound spectrograph having a frequency analyzer means that simulates the characteristics of the human ear, particularly with regard to the ability of the ear to distinguish tonal differences and with regard also to the response of the ear to rapid changes in the strength of the several components of a complex sound. In accordance with this feature the selectivity, or band width, of the

3

frequency analyzer element of the spectograph is designed to conform with that of the frequency selective elements of the ear. More particularly, the spectograph may be designed to have a certain frequency resolution, uniform over the audio frequency range of interest and approximating the average frequency resolution of the ear over the same range, or it may have a frequency resolution that varies over the frequency range in closer conformity with the varying frequency resolution of the ear. In accordance with this feature also, the time resolution of the spectograph, i. e., the faithfulness with which the device responds to time variations in effective intensity, substantially matches the imperfect response characteristic of the ear. The frequency analyzer means, which may be a band-pass filter, for example, like the ear, does not respond instantly to a sudden change, in either direction, in the effective intensity of a component. In both cases the intensity builds up or decays gradually, and at a rate correlated with the frequency resolution.

In accordance with another feature of the invention a sound spectograph is designed to produce a spectrogram in which the frequency scale is logarithmic, whereby frequency components in octave relation are represented at equally spaced positions along the frequency scale in further simulation of human hearing. A more particular feature of the invention lies in the concurrent production of a logarithmic frequency scale and frequency resolution that varies with frequency. With these features incorporated in the spectograph it is found that the visual representations of the various speech sounds take on distinctly different characteristic shapes which some regard as easier to read than the representations obtained when a linear, or uniform, frequency scale is employed. Furthermore, when spectrograms of music are produced in accordance with these features equal prominence is given the musical activity in all octaves and the spectrograms are otherwise, too, aesthetically proper and pleasing.

Still another feature of the present invention is a sound spectograph in which the band width of the analyzing means is wide enough to embrace a plurality of successive harmonics of the fundamental voice frequency or is at least comparable with the frequency spacing of such harmonics. This feature yields a high degree of time resolution and a more easily readable translation of various unvoiced speech sounds, such as those of explosive character. A related feature, involving overlapping of the frequency bands selected by the analyzing means, yields a speech spectrogram in which the relative positions and widths of the several resonance regions associated with voiced sounds are clearly pictured without the unnecessary and distracting detail of the harmonic structure of such sounds. The provision of a logarithmic frequency scale in such case serves to exaggerate the resonance shifts in the low frequency region.

In accordance with another feature of the invention any desired component frequency band of a complex wave is caused to be selected by a single, fixed band-pass filter or the like by recording the complex wave and reproducing the recorded wave at a predetermined rate of reproduction. The recorded wave, further, may be reproduced at successively different rates to pass successively different component bands through the filter and effect a complete frequency analysis of the wave.

4

The nature of the present invention, and its various objects and features including those hereinbefore mentioned, will appear more fully from a consideration of the several embodiments of the invention that are illustrated in the drawings and from the following detailed description thereof. In the drawings, Figs. 1, 2 and 3 show three different forms of spectograph in accordance with the invention and Figs. 4, 5 and 6 represent typical spectrograms produced thereby.

Referring now to the sound spectograph that is illustrated schematically in Fig. 1, the complex sound-bearing waves that are to be translated into visual form are first stored in reproducible form. Arriving over microphone circuit 1, these waves are applied through switch 2 to the recording coil 3 of a magnetic recorder-reproducer. The latter may be of any well-known type and is symbolized in Fig. 1 by an endless magnetic tape 4 mounted on a motor-driven disc 5 and arranged to pass between the pole-pieces of the recorder. Once the waves are recorded the recorder-reproducer plays them back, or electrically reproduces them, over and over again.

On moving switch 2 to its alternate position, as shown, the reproduced waves are applied to a frequency scanner or heterodyne analyzer comprising elements 6, 7 and 8. The element 8 is a band-pass filter, a frequency selective device that passes any wave having a frequency that falls within its pass-band. Modulator 6 and its associated beating oscillator 7 together constitute a frequency translator, by means of which the applied complex waves can be shifted to a higher frequency range dependent on the operating frequency of oscillator 7. The oscillator frequency is progressively changed from one reproduction of the recorded waves to another so that progressively different parts of the complex wave band are made to coincide with the pass-band of filter 8. In the course of producing a single spectrogram the entire complex wave band is moved gradually from one extreme position to another, across the pass-band of filter 8. In effect, the heterodyne analyzer scans the frequency range occupied by the complex waves and selects the wave components that appear in progressively different parts thereof. The oscillator frequency may be changed at the end of each reproduction or it may be changed continuously, the slight change in frequency that occurs during any one reproduction being insignificant in the latter case. As indicated schematically in the drawing, oscillator 7 may be varied in frequency in synchronism with the movement of a threaded nut 9 that moves longitudinally on a threaded shaft 10 which, in turn, is rotated in synchronism with the magnetic recorder disc 5.

The record surface in the Fig. 1 system is a strip of facsimile paper 13 that is wrapped once around a cylindrical metal-faced drum 14 which is driven in synchronism with disc 5 and shaft 10. The facsimile paper may be a titanium oxide-carbon recording paper such as the "Teledeltos Grade H" facsimile paper developed by the Western Telegraph Company.

A wire stylus 12 that bears against the recording surface of the facsimile paper 13, is so linked with the traveling nut 9 that it moves once across the facsimile paper 13, i. e., parallel to the axis of drum 14, in the course of production of a single spectrogram. Each position of the stylus 12 cross-wise of the strip of paper 13 is therefore identified with a respectively corresponding setting of the frequency of oscillator 7 and with a particu-

5

lar component frequency band selected by the heterodyne analyzer. The wave output of filter 8 may be applied directly to stylus 12 or indirectly through an amplifier-rectifier 11. In either case the current applied to stylus 12 causes the facsimile paper to darken at the point of contact to a degree dependent on the strength of the applied current. The marking current varies in strength in accordance with the variations in the effective intensity or power content of the particular component band passed by filter 8.

In view of the foregoing description of the Fig. 1 system it will be understood that while the recorded waves are being reproduced once the stylus 12 traverses a substantially longitudinal or circumferential path on the facsimile paper 13 and records along that path, by variations in darkness or blackness, the variations in wave power content found in a particular frequency band selected by filter 8. The operation continues until the entire frequency range of interest has been scanned and the spectrogram has been completely built up line by line.

In one instance in practice speech waves were recorded for 2.4 seconds on the magnetic tape 4 and then played back 200 times while the frequency scanner progressed at uniform rate through a frequency range extending from about 200 to 3700 cycles per second. The transverse movement of the stylus 12, a wire 10 mils in diameter, was 2 inches, and the circumferential length of the paper 12 was about 12 inches. Filter 8 was assigned a mean pass frequency of about 12,000 cycles and several different band widths were employed. A filter having an effective band width of about 45 cycles was judged to afford the closest approximation to the frequency resolution of the ear, over the frequency range of interest, and the closest approximation also to the time resolution or transient characteristic of the ear.

Fig. 4 illustrates the nature of the spectrogram that was obtained when the 45-cycle filter was used. The vertical or transverse dimensional coordinate has the sense of a linear frequency scale and is so indicated in Fig. 4. Likewise, the horizontal or longitudinal dimensional coordinate has the sense of a time scale. The longitudinal path traversed by the stylus while a particular component frequency band was being selected is indicated at F and the blackness of the pattern varies along the length of this path more or less in proportion to the varying power content of that component band. The vertical strip T represents a particular time interval, and along this strip the variations in blackness of the recording represent the frequency composition, or distribution of total wave power, during that interval. Further, the blackness of the recording in the typical elemental area at the intersection of F and T is a measure of the power content appearing in the frequency band F during the time interval T. Negative and positive reproductions of the spectrogram may be made on photographic film by conventional photographic processes; or by employing an optical stylus in lieu of stylus 12, as disclosed in my first-mentioned application, the spectrogram may be formed directly on film.

Increased frequency resolution may be had by reducing the band width of filter 8. The attendant loss of time resolution may be relatively unimportant for some applications of the invention and quite insignificant in cases where the strength of the frequency components does not change abruptly.

Where one's purpose is to produce a speech

6

spectrogram that can be read relatively easily, substantial advantages are gained by making the band width of the scanning filter 8 several times greater than the value suggested above. The improved time resolution that accompanies use of the wider band has the effect of better confining the visual representation of sudden speech sounds to the proper time-position in the spectrogram, i. e., the time boundaries are more sharply defined. Further, less relative attenuation is suffered by the usually weak components of a suddenly changing sound, and relatively more wave energy is therefore available for application to the recording elements. The reduction in frequency resolution is advantageous also in that details of the harmonic structure of the voiced sounds are suppressed in the spectrogram and only the basic outline of the visual equivalent appears distinctly. A vowel sound, for example, comprises the fundamental voice frequency, which may be as high as 250 cycles per second for female voices, and all of the harmonics thereof, but the wave power is largely concentrated in a few, usually one to four, parts of the frequency range, each part corresponding to one of the principal resonances of the vocal cavities and each embracing a plurality of successive harmonics. By making the pass-band of the scanning filter wide enough to embrace two successive harmonics, so that at least one harmonic always falls within the pass-band of the filter while the analyzer scans the principal resonance regions, the individual harmonics in any such region will be recorded only indistinctly if at all, but the resonance region itself will be clearly defined.

A related feature contributing to legibility of the speech spectrogram lies in the fact that each frequency component is selected during each of a plurality of successive reproductions or, otherwise stated, it lies in the relatively large ratio of filter band width to the incremental change in oscillator frequency. The latter, in the specific example described herein, is $17\frac{1}{2}$ cycles, while the filter pass-band may be a few hundred cycles wide.

Fig. 5 illustrates the nature of a speech spectrogram that was produced by a system conforming substantially with Fig. 1 in which the scanning filter 8 had a pass-band 300 cycles wide. Successive horizontal strips each approximately 0.01 inch wide are respective to the successively different, although overlapping, component frequency bands each 300 cycles wide. Each vertical strip across the pattern, as in Fig. 4, displays the frequency composition or energy distribution of the complex wave without detailing the variation from one harmonic to another. The regularly spaced vertical striations in Fig. 5 are associated with voiced sounds and are due to the beating effect that results from the concurrent selection and recording of a pair of successive harmonics of the fundamental voice frequency. The difference or beat frequency arising from any such pair of harmonics is the same throughout the speech frequency range, and it is equal to the fundamental frequency. The straightness of the striations is an indication that the phase relations, or wave shape, at the vocal cords is constant.

To reduce the time required to produce a spectrogram with the Fig. 1 system, the rate at which the magnetic tape 4 is driven may be increased at least several-fold after the complex waves have been recorded. For specific example, the rate of

reproduction may be three times the rate of recording. This results in a three-fold expansion of the frequency range occupied by the complex wave, and corresponding changes in the proportioning of the elements of the frequency spanner are required.

Fig. 2 illustrates a modification of the sound spectrograph system shown in Fig. 1, in which provision is made for varying the frequency resolution automatically as a function of frequency, and in which a logarithmic or other non-linear frequency scale is obtained. Corresponding elements in the several figures have been assigned the same reference characters. The magnetic tape 4 and the facsimile paper 13 are shown in Fig. 2 in the form of long belts, driven in synchronism with each other, and adapted to accommodate a longer sample of the complex waves to be recorded and visually represented. The principal circuit changes are the substitution of a band-pass filter 18 having a pass-band of adjustable width, in lieu of the fixed scanning filter 8, and the provision of an amplifier 19 of adjustable gain in lieu of the amplifier-rectifier 11 of Fig. 1.

The stylus 12 is driven across the facsimile paper 13 in Fig. 2 by a follower 20 that rides on a rotary cam 21 which is driven, by means of a mechanical linkage including a worm gear 22 on the drum shaft and a pinion 23, at a slow rate in synchronism with the movement of paper 13. The rate of movement of stylus 12 depends on the contour of cam 21 and it may be made uniform or non-uniform as desired. That is, the displacement of stylus 12 from its initial position may be made a linear function of time or a non-linear function of time such as logarithmic for specific example, by insertion of the properly shaped cam. Elements 7, 18 and 19 are automatically varied in synchronism with the repeated reproduction of the recorded waves by any suitable mechanical system such as one including a rack 24 driven by pinion 23 and connected through any suitable system of mechanical linkages to the devices for adjusting the several elements.

The operating frequency of beating oscillator 7 is advantageously varied as a linear function of time independently of the law of movement of stylus 12; or in other words, the oscillation frequency is changed by the same amount from any one reproduction of the recorded waves to the next. The band width of filter 18 is so varied, at a linear rate, that it is maintained at a constant percentage of the mean frequency of the audio frequency band selected by the analyzer at any time. That is, the band width is always directly proportional to the mean frequency of the component frequency band corresponding to the position of stylus 12 along the frequency scale of the spectrogram. The rate at which the gain of amplifier 19 is varied is dependent on the rate of movement of stylus 12 and is calculated in any particular case to approximately equalize the intensity of the recording in the several parts of the frequency scale of the spectrogram. In general, the gain of the amplifier should be maintained at a relatively low value while the stylus 12 moves slowly and at a higher value while the stylus moves rapidly.

In accordance with an important feature of the present invention, as it is embodied in the system shown in Fig. 2, the stylus 12 is moved at a logarithmic rate from the low frequency edge of the spectrogram to the high frequency edge

thereof. This requires that the contour of cam 21 produce a displacement of stylus 12 that is an exponential function of time. In such case the frequency scale of the spectrogram is logarithmic, that is, equal intervals along the scale represent equal percentage changes in frequency. The stylus 12 may be started at the high frequency edge of the spectrogram if desired by reversing the direction of rotation of cam 21 and reversing also the sense of variation of the several variable circuit elements.

The logarithmic frequency scale is especially desirable where spectrograms of music are to be projected on a screen to serve as a visual interpretation of and accompaniment for acoustic reproduction of the same music. For this field of use the spectrograms are produced or reproduced on film, and either as a longitudinally continuous record or frame by frame depending on the type of projector to be used. If a linear frequency scale were used most of the action would be squeezed into the lower frequency part of the spectrogram. The middle of the piano keyboard, for example, is roughly 500 cycles whereas on a spectrogram capable of showing up to 5,000 cycles with a linear frequency scale, 500 cycles would be only one-tenth the width of the spectrogram from the low frequency edge thereof. Hence, if the notes of a musical composition were equally distributed either side of the center of the piano keyboard, half of the action would be compressed within the bottom one-tenth of the spectrogram frequency scale and the rest spread thinly over the remaining nine-tenths. With a logarithmic or octave scale, on the other hand, all of the octaves are given equal prominence, each occupying the same space as any other.

In the spectrogram with linear frequency scale, the harmonics that make up any piano or other musical note are spaced at regular intervals. In a spectrogram with an octave frequency scale the same harmonics are spaced in a logarithmic relation, those in the upper range being squeezed progressively closer together. The second, fourth, eighth, sixteenth, etc. would be spaced at regular intervals so that only one, the third, would appear between the second and fourth, while in an equal space between the eighth and sixteenth, seven would appear. Due to the fact that progressively more than one harmonic will fall within the scanning filter for the higher frequencies the harmonic series will become blurred and the components merged in this region. The graduated process will also produce pattern effects. In a true octave scale, it may be noted, all harmonic patterns would look alike regardless of fundamental frequency if the complex waves are otherwise of the same composition. As the composition varies the harmonic pattern will undergo changes in shape. It may well be, too, that the results of this logarithmic spacing of harmonics will be regarded as more pleasing than the regular spacing afforded by the linear frequency scale.

With regard to the band width of the scanning filter 18 it will be understood that use of a constant band width and an octave frequency scale results in tone traces that are substantially broader at the low frequency end of the scale than at the high frequency end. In fact the width of a tone trace is halved for each octave in the high frequency direction. This effect is avoided if the scanning filter band width is a constant fraction of the frequency at any point along the frequency scale. Thus the band width may be one-tenth of the frequency or 7 cycles at 70 cycles,

50 cycles at 500 cycles, 400 cycles at 4000 cycles, etc. In such case the width of a tone trace is the same regardless of its position in the frequency range. Furthermore, variations in the band width of the scanning filter, and therefore also of the frequency resolution, enables the spectrograph to simulate more closely the frequency resolution of the human ear. The latter varies with frequency approximately logarithmically and can be simulated with a scanning filter the band width of which is approximately 10 per cent of the mean frequency of the band selected from the original sound waves. If the band width is made substantially greater than the value here suggested, the frequency resolution becomes so poor that tones that can be easily separated by the ear are confused in the spectrogram. Too narrow a pass-band on the other hand so impairs the time resolution that the time variations in amplitude indicated in the spectrogram do not correspond to the audible sound effects and are more protracted. The resolution of the ear is not a strictly logarithmic function of frequency, however, and a slightly closer simulation can be had if the band width of the scanning filter is made somewhat greater than the logarithmic value at both the low and high frequency ends of the range.

The visual pattern or phonetic symbol for each speech sound has a certain characteristic appearance that depends on whether a linear or logarithmic frequency scale is employed. The distinguishing characteristics of certain speech sounds appear to be brought out more distinctly where the logarithmic scale is employed.

Fig. 6 is an approximate illustration of a speech spectrogram produced in accordance with the principles embodied in Fig. 2 and having a logarithmic frequency scale.

In accordance with a modification of the Fig. 2 system the stylus 12 may be driven at a linear rate while the operating frequency of oscillator 7 is varied at a progressively increasing rate such that a logarithmic frequency scale obtains in the spectrogram. In this case the stylus 12 traverses the same number of longitudinal paths per octave. The concurrent variation in the band width of filter 18 results in tone traces that are of equal width regardless of their position along the frequency scale.

Fig. 3 illustrates a sound spectrograph in accordance with the present invention in which the frequency analysis of the reproduced waves is effected, with the aid of a single fixed filter 8, by varying the rate at which the complex waves are reproduced. The variable frequency translating equipment, comprising modulator 6 and variable frequency oscillator 7 in Fig. 1, is entirely dispensed with. Furthermore, the frequency resolution of the analyzer is automatically varied without changing the actual band width of filter 8.

Included in the Fig. 3 organization is any suitable mechanism for progressively changing the rate at which the recorded waves on magnetic tape 4 are reproduced while the complete spectrogram is being built up on the facsimile paper 13. Such a mechanism is diagrammatically illustrated as comprising a conical pulley 30 rotated at constant speed, an oppositely tapering conical pulley 31 on a separate parallel shaft, and, connecting the two, a belt 32 which is shifted along the length of the pulleys by a belt shifter 33. The latter is advanced by means of a follower 34 which

is adapted to engage the feed screw 10 that connects pulley 31 and drum 14.

The complex waves received in input circuit 1 are first recorded on magnetic tape 4 in the usual manner and at normal rate, with follower 34 disengaged and the belt shifter 33 manually positioned to give the proper rate of tape movement. The belt shifter 33 is then moved to a starting position at the left-hand extremity of the pulleys, follower 34 is adjusted to engage the feed screw 10, and reproduction and recording begin. The initial rate of reproduction is substantially less than the normal rate, but as belt 32 is gradually shifted to the right the rate of reproduction gradually increases and reaches a final value that is substantially greater than the normal rate.

When the recorded waves are reproduced at normal rate they are in all respects the same as the waves applied to the recorder, but when they are reproduced at any other rate they differ in respect of the position and extent of the frequency range they occupy. If they are reproduced at a rate n times the normal rate the frequency of each reproduced component becomes n times the original frequency; the frequency band occupied by the waves, originally f_1 to f_2 , is raised and expanded to the range nf_1 to nf_2 ; and the width of each component frequency band is likewise expanded n times. Correspondingly, if the rate of reproduction is less than normal the various frequencies are reduced and the band widths are contracted in the same proportion. Hence, by appropriately adjusting the rate of reproduction, any component of the recorded waves may be translated to a frequency within the pass-band of filter 8, and all components may be successively presented to and selected by filter 8 by successively changing the rate of reproduction.

The principle of operation of the frequency analyzer component of the Fig. 3 system may be further explained with reference to a specific example. Suppose that the frequency range of interest extends from a frequency f_1 of 300 cycles per second to a frequency f_2 of 4800 cycles per second, the mean frequency of this range being $\sqrt{f_1 \cdot f_2}$ or 1200 cycles per second. Filter 8 is designed to have the same midband frequency, 1200 cycles per second, and a band width to afford the desired resolution, e. g., a band width of 120 cycles. The rate of reproduction is varied from $\sqrt{f_1/f_2}$, or one-quarter of the normal rate, to $\sqrt{f_2/f_1}$ or four times the normal rate. At the initial, reduced rate, n being $1/4$, the 4800-cycle component of the recorded waves appears at 1200 cycles in the reproduced waves and it is therefore passed by filter 8. As the rate is increased from one reproduction to another, other components are successively selected by the filter until during the final, accelerated reproduction, when n is 4, the 300-cycle component appears in the pass-band of filter 8 and is selected thereby.

The frequency resolution is inversely proportional to the rate of reproduction. During the first, low-speed reproduction a 480-cycle band of waves having a mean frequency of about 4800 cycles per second is compressed to the 120-cycle band width of filter 8. During successive reproductions progressively narrower component bands are compressed, or expanded, to occupy the pass-band of the filter. The highest frequency resolution is obtained during the last, high speed reproduction when the band passed by filter 8 is derived from a 30-cycle band having a mean frequency of about 300 cycles per second. The ef-

fective band width or selectivity of the frequency analyzer is thus virtually varied to maintain the desired, constant one-to-ten relation between the width of each band selected from the recorded waves and the mean frequency of the selected band.

The rate at which the frequency analyzer progresses across the frequency range, f_1 to f_2 , depends on the rate at which the rate of reproduction is changed. Thus, the rate of reproduction may be changed, continuously or in steps, by the same amount from any one reproduction to the next whereby the mean frequencies selected during successive reproductions all differ from each other by the same number of cycles. Any desired different rate of progression may be obtained by altering the shape of the pulleys 30 and 31.

The wave effects appearing in the output circuit of filter 8 are applied to the stylus 12 of the recorder, and an amplifier or an amplifier-rectifier 11 may be interposed in the connection if desired.

Although the drum 14 carrying the facsimile paper 13 rotates at a progressively changing rate, it will be understood that the stylus 12 nevertheless traverses one substantially circumferential or longitudinal path across the paper during each reproduction of the recorded waves. Stylus 12 may be directly connected to the follower 34, in which case its rate of movement crosswise of the paper 13 is the same as the rate of movement of the follower, or a mechanical linkage system comprising rack 35, pinion 23 and cam 21 may be interposed between the two to obtain any desired law of stylus movement. The latter affects the frequency scale, which may be made uniform, or logarithmic, or otherwise, as desired.

In practice it may be found desirable to employ a filter 8 having a pass-band that lies substantially above the highest frequency component of the recorded waves. In such case a fixed frequency translator, comprising modulator 36 and beating oscillator 37, as illustrated in Fig. 3, may be used to translate the reproduced waves to a higher frequency range before they are applied to the filter. The frequency translator may be arranged to be plugged into the connection between reproducer coil 3 and filter 8 after the complex waves have been recorded on tape 4. Switch 38 is provided for this purpose. The varying rate of reproduction is relied upon as before to advance the band of reproduced waves across the pass-band of filter 8. The frequency translator 36—37 may be employed also to translate super-audible complex waves to an audio frequency range suitable for recording on the magnetic tape 4.

With a view to compensating for the limited recording range of the facsimile paper 13, amplitude compression of the varying current delivered to stylus 12 may be incorporated in any of the spectrographs herein disclosed. Frequency equalization also may help to insure that all values of marking current are recorded as different degrees of darkness or blackness on the facsimile paper.

Although the present invention has been described largely with reference to the several specific embodiments herein disclosed it will be evident to those skilled in the art that the invention may be embodied in various other forms within the spirit and scope of the following claims.

What is claimed is:

1. A speech spectrograph comprising means for receiving speech-bearing waves, frequency an-

alyzer means for resolving the said waves into a multiplicity of component frequency bands substantially all of which are wide enough to embrace two successive harmonics of the fundamental speech frequency, and means for translating said waves into a visual representation the dimensions of which have the sense of coordinate axes representing frequency and time, respectively, comprising a surface on which the representation is to appear, and means responsive to the wave components selected by said analyzer means for visually representing on said surface, in different coordinate positions respective to the different component frequency bands, the variations in the wave power content of each of said frequency bands.

2. A speech spectrograph in accordance with claim 1 in which each of said component frequency bands is in overlapping relation with at least several adjacent ones.

3. In combination, means for recording complex waves, means for repeatedly reproducing the recorded complex waves, frequency analyzer means for selecting a band of waves from the reproduced waves, means for progressively changing the frequency band that is selected by said analyzer means at a rate of change such that a given frequency component is selected during each of at least several successive reproductions of the recorded waves, and stylus means for visually recording the variations in the wave power content of each selected frequency band along one of a multiplicity of laterally adjacent lines on a record surface each of which lines is individual to a respectively corresponding frequency band.

4. A speech spectrograph in accordance with claim 3 in which the width of the selected band is from two to three times as great as the fundamental speech frequency.

5. A combination in accordance with claim 3 including means for selecting from the recorded waves successively different frequency bands the widths of which are progressively different.

6. A combination in accordance with claim 3 including means for progressively changing the rate of reproduction of the recorded waves from one reproduction to another.

7. A combination in accordance with claim 3 in which the frequency resolution of said selecting means approximates the frequency resolution of the human ear.

8. A combination in accordance with claim 3 in which the said rate of change and the spacing of said lines are so correlated that frequency bands having harmonically related mean frequencies are recorded along equally spaced lines.

9. In combination, means for receiving sound-bearing waves, means for deriving from the received waves a multiplicity of effects each varying in accordance with the varying wave power content of a different component frequency band, said frequency bands being of different widths increasing progressively with increasing mean frequency, means for visually representing the composition of said waves in the form of a pattern the dimensions of which have the sense of a time scale and a substantially logarithmic frequency scale, respectively, said last-mentioned means including stylus means, movable relative to and across a record surface, for marking the amount of wave power appearing in any of said frequency bands at any time in the coordinate position respective to the particular band and time.

10. A combination in accordance with claim 9

in which the width of each said frequency band is approximately ten per cent of its mean frequency.

11. In combination with a recording of complex waves, means for repeatedly reproducing the recorded waves at a rate of reproduction that changes progressively and substantially continuously in the course of a series of reproductions, frequency selective means operative on the reproduced waves for selectively transmitting progressively different parts thereof, and means responsive to the said selectively transmitted parts for producing a visual representation of the frequency composition of said waves, one of the dimensions of the representation having the sense of a frequency scale.

12. A frequency analyzer comprising wave-responsive recording means for recording waves to be analyzed, means for repeatedly reproducing the recorded waves in the form of electrical waves, means for progressively changing the rate of reproduction to translate the various components of said waves successively to substantially the same position in the frequency range, and receiving means connected to selectively receive the translated components appearing successively at said position in the frequency range.

13. A complex wave analyzer comprising magnetic recording means for storing the waves to be analyzed, means for repeatedly reproducing the stored waves and progressively changing the rate of reproduction, frequency selective means for receiving the reproduced waves and selecting energy from progressively different component frequency bands thereof, and a device responsive to the said selected energy and synchronized with said rate changing means for displaying the frequency composition of said waves.

14. The method which comprises recording a complex electrical wave of unknown frequency composition, reproducing the recorded wave in electrical form, varying the rate of reproduction substantially continuously over a range wide enough to bring the different frequency components of the recorded wave in succession to a predetermined fixed position in the frequency range, and selecting the said components from the reproduced waves as they appear in succession at said fixed position in the frequency range.

15. In combination, means for recording complex waves, means for repeatedly reproducing the recorded waves at a progressively changing rate of reproduction, frequency selective means for receiving the reproduced waves and selecting progressively different components thereof in succession, stylus means for marking on a rec-

ord surface, means for moving said stylus means relative to and across the record surface along a multiplicity of collateral paths in succession and in timed relation to the successive selection of different components, and means for varying the mark made by said stylus means in response to variations in the intensity of the selected component.

16. In combination, means for storing complex waves, means for repeatedly reproducing the stored waves at a substantially uniform rate, frequency selective means operative on the reproduced waves for selecting progressively different frequency bands therefrom during respectively corresponding successive reproductions thereof, means for progressively changing the width of frequency band selected by said frequency selective means, a marking stylus movable relative to and across a record surface, means for relatively displacing said stylus repeatedly in one direction across said surface in synchronism with the repeated reproduction and progressively in another direction, and means for applying to said stylus a marking current that varies in intensity in correlation with the variations in wave power content of the selected frequency band.

17. A combination in accordance with claim 16 comprising means for displacing said stylus progressively in said other direction at a substantially logarithmic rate.

18. A combination in accordance with claim 16 including means for additionally varying the intensity of the said current applied to said stylus as a function of the displacement of said stylus in said other direction.

19. A record bearing a permanent visual representation of complex waves in the form of a pattern the dimensions of which have the sense of a time scale and a logarithmic frequency scale, respectively, the pattern differing from one point to another to represent differences in the intensity of the wave components, and the pattern definition varying along the frequency scale as an inverse function of frequency.

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