Sept. 15, 1970 E. M. JONES 3,529,070

ELECTRICAL MUSICAL INSTRUMENT PROVIDED WITH WAVE FORM MODULATION

Filed June 16, 1966

5 Sheets-Sheet 1

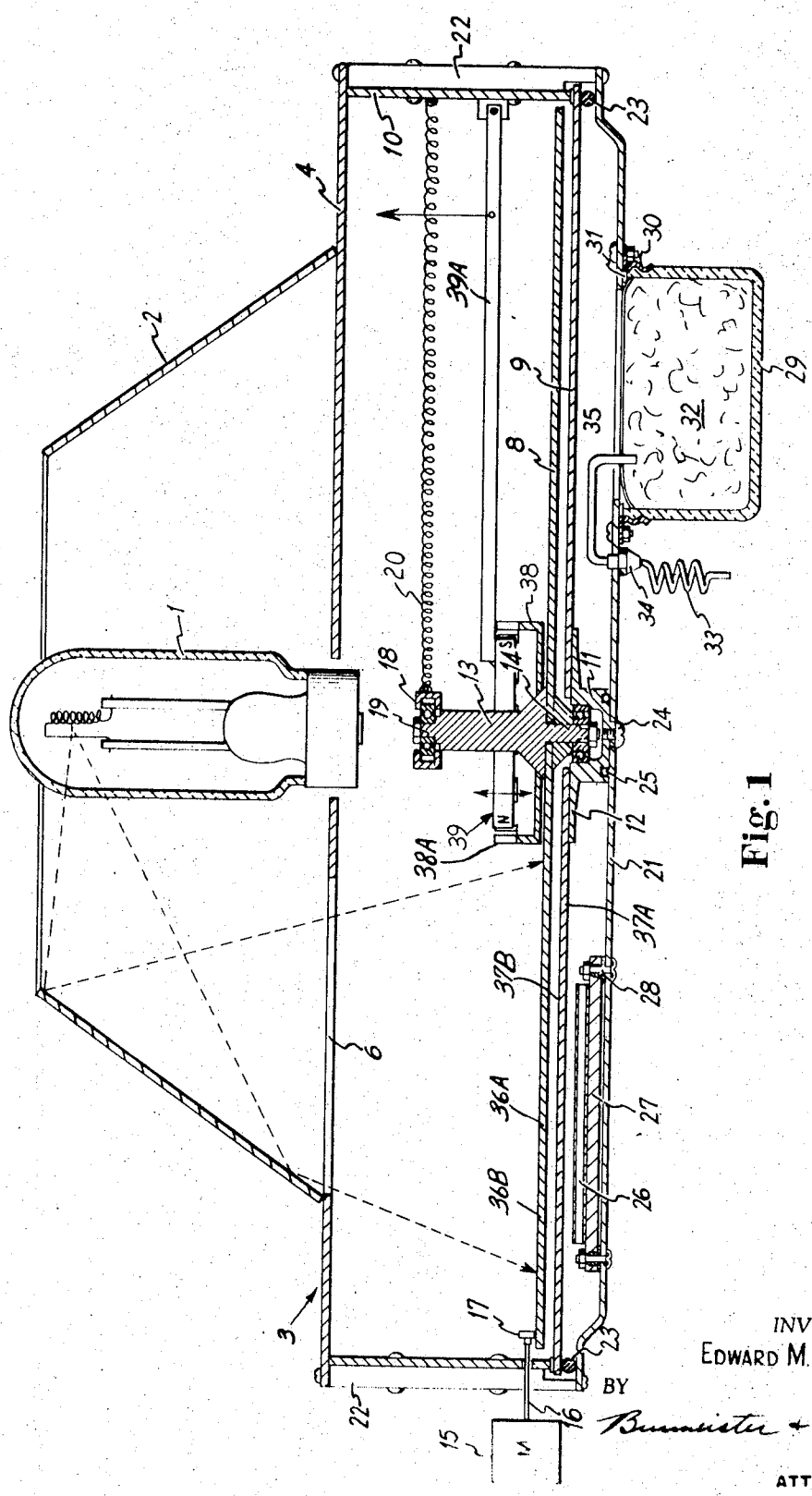


Fig. 1

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ELECTRICAL MUSICAL INSTRUMENT PROVIDED WITH WAVE FORM MODULATION

Filed June 16, 1966 5 Sheets-Sheet 2

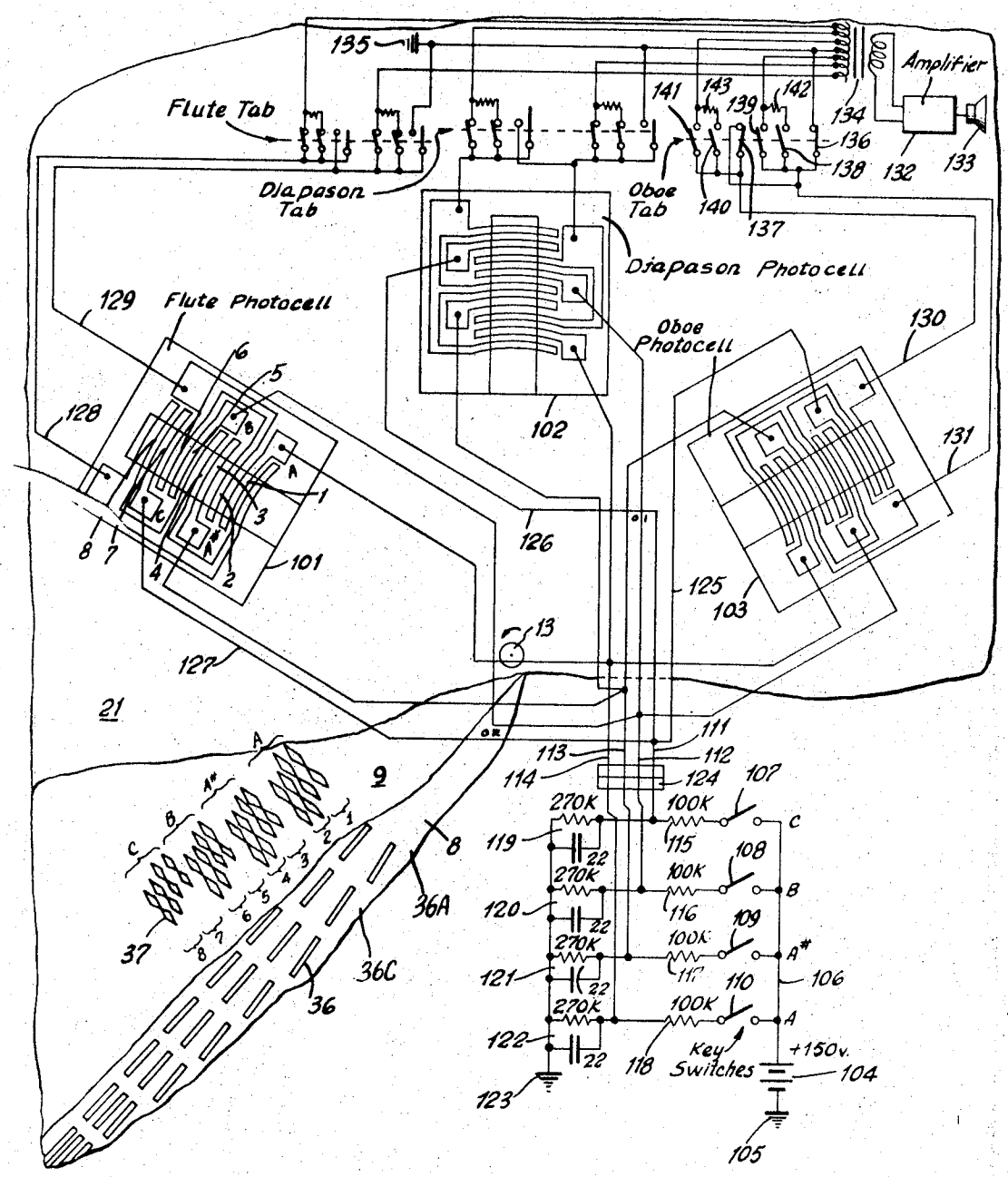


Fig. 2

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ELECTRICAL MUSICAL INSTRUMENT PROVIDED WITH WAVE FORM MODULATION
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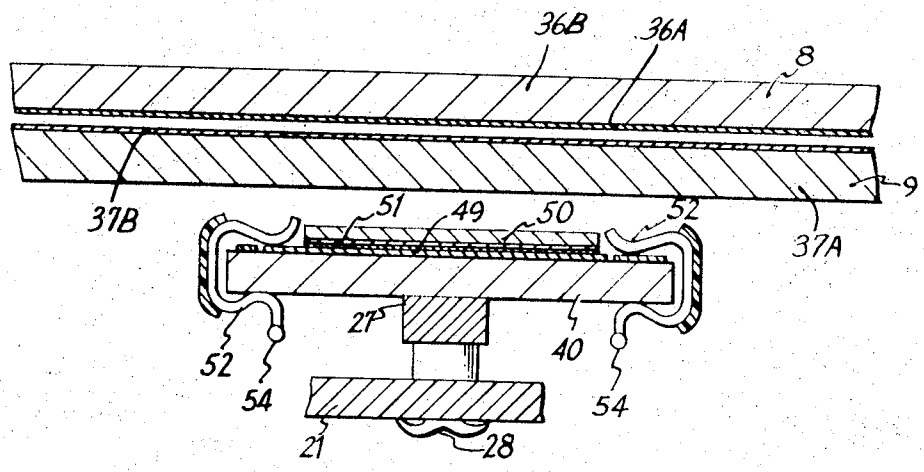


Fig. 3

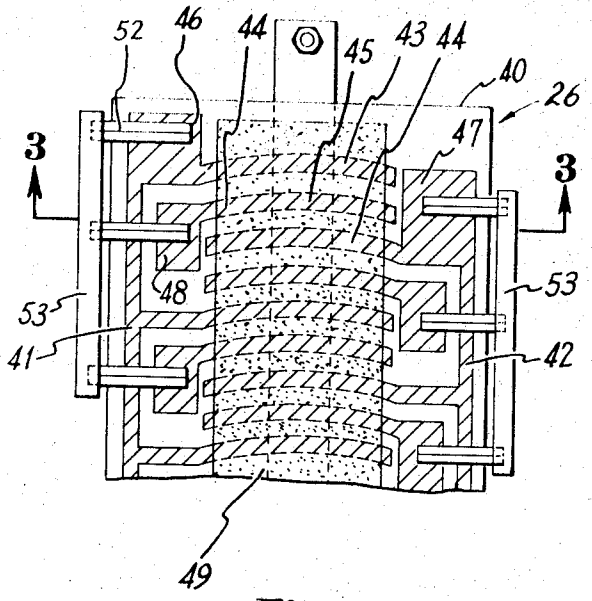


Fig. 4

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Fig.5

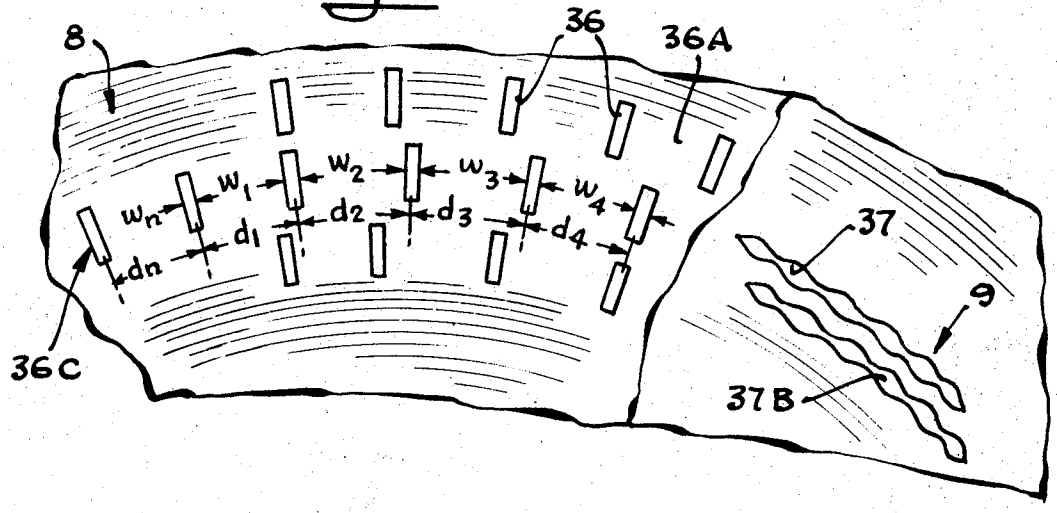
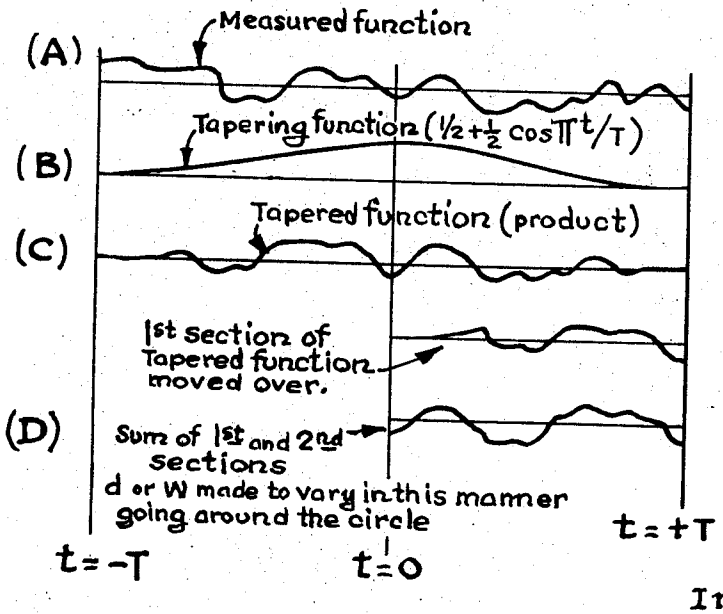


Fig.6



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ELECTRICAL MUSICAL INSTRUMENT PROVIDED WITH WAVE FORM MODULATION

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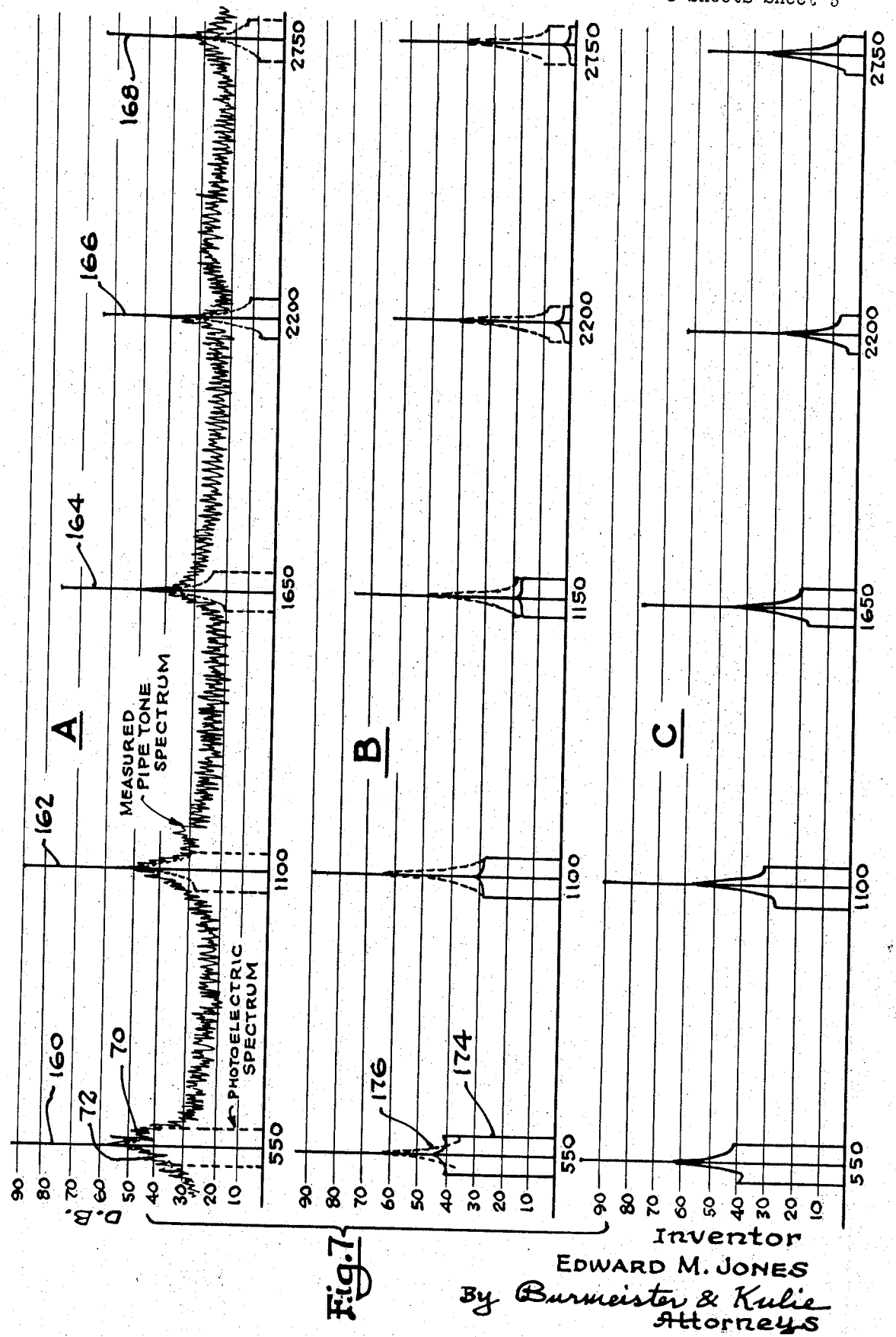


Fig. 7

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United States Patent Office 3,529,070 Patented Sept. 15, 1970

3,529,070

ELECTRICAL MUSICAL INSTRUMENT PROVIDED WITH WAVE FORM MODULATION

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Filed June 16, 1966, Ser. No. 557,958
Int. Cl. G10h 3/04, 1/01
U.S. Cl. 84—1.28 15 Claims

ABSTRACT OF THE DISCLOSURE

An electrical musical instrument having a tone generator for generating an electrical signal for each note to be produced in which the frequency of the electrical signal is modulated as to amplitude and as to frequency at a rate less than 1/50 of the frequency of the electrical signal. In the illustrated embodiment, the electrical signals are generated photoelectrically using a pitch disc and a tone disc in which the size and spacing of transparent areas in the pitch disc are used to frequency and amplitude modulate the electrical signal.

This invention is an improvement on the organ of Pat. No. 3,249,678 entitled "Photoelectric Organ and Appurtenances." The present invention relates to devices for controlling the tone quality of electrical musical instruments, and in particular to means for controlling the side band amplitude of tones produced by electrical musical instruments.

Electrical musical instruments have long attempted to imitate the tones produced by a pipe organ. It has been found that merely controlling the harmonic content of the tones produced by an electrical musical instrument will not succeed in imitating the tones of a pipe organ. One of the objects of the present invention is to provide an electrical musical instrument with a means for controlling additional parameters of the tones produced in order to more closely imitate the tones of a pipe organ, or to produce tones of different voice colors than can presently be accomplished.

The inventor has found that the side band content of a tone produced by an electrical organ may be controlled in order to produce voices other than those known to the prior art. Further, the inventor has found that by controlling the side bands of a tone produced by an electrical musical instrument the tones of a pipe organ may be imitated. It is therefore an object of the present invention to provide a means for adding side bands to the tones of an electrical musical instrument and for controlling their amplitude. It is particularly an object of the present invention to provide a photoelectric organ with tones containing side bands of controlled amplitude.

In addition to these objects, it is an object of the present invention to provide an electrical musical instrument with tones containing side bands of controlled amplitude in which the cost of controlling the side band amplitude is minimized, and in which the means for producing and controlling the side bands of the tones of the instrument is reliable and unlikely to produce operational failures.

These and further objects of the present invention will become readily apparent to those skilled in the art from a further consideration of this specification, particularly when viewed in the light of the drawings, in which:

FIG. 1 is a sectional view of the tone generators of an electric organ, the figure being partly diagrammatic;

FIG. 2 is a diagrammatic view of a portion of the tone generators of FIG. 1 of the electric organ, and further illustrates diagrammatically the electrical circuits of the electric organ of FIG. 1;

FIG. 3 is an enlarged fragmentary sectional view of a portion of the electric organ of FIGS. 1 and 2 illustrating the photocell assembly, the voice plate, and the pitch disc thereof;

FIG. 4 is an elevational view of the photocell assembly illustrated in FIGS. 1 through 3;

FIG. 5 is an enlarged fragmentary view of a portion of the pitch disc and tone plate of the organ illustrated in FIGS. 1 through 3;

FIG. 6 is a graph showing in curve (A) the measured amplitude modulation of the C♯5 diapason tone of a pipe organ, in (B) a tapered mathematical function of the same time period, and in (C) a curve representing a continuous mathematical function corresponding to the amplitude modulation of the C♯5 diapason tone of a pipe organ; and

FIG. 7 at A illustrates the most significant portion of the measured spectrum of the C♯5 diapason tone of a pipe organ, at B illustrates the tones produced by a photoelectric organ showing amplitude modulation produced side bands separately from frequency modulation produced side bands, and at C the spectrum of the same photoelectric organ with the frequency modulation produced side bands and the amplitude modulation produced side bands combined in out of phase relation.

While the present invention may be practised with various types of electric organs, such as photoelectric, electrostatic, and even reed type organs, it is particularly adapted to photoelectric organs and is illustrated in FIGS. 1 through 4 in a photoelectric organ embodiment. As best illustrated in FIG. 1, the photoelectric organ, or musical instrument, has a lamp **1** and a reflector **2** constituting a source of illumination or light source. The lamp **1** and reflector **2** are mounted on a housing **3** which has an upper plate **4** including a plurality of openings **6** which permit light to enter into the housing **3**. Light from the light source passes through the openings **6** to impinge and traverse a pitch disc **8** and thereafter a voice disc **9**. The voice disc **9** is stationary within the housing **3**, and a wall **10** which is circular in the particular embodiment disclosed surrounds the voice disc **9** and forms a protective enclosure with the other elements of the housing **3**.

The voice disc **9** carries at its center a structure **11** which has a flange **12** cemented on the voice disc. The pitch disc **8** is provided with a spindle **13** having a lower extension **14** which is mounted in a ball bearing in the structure **11**. The pitch disc **8** and voice disc **9** are preferably constructed of glass and are provided with a coating preferably by a photographic method which forms transparent and opaque areas, as will be more fully described hereinafter.

The pitch disc **8** is rotated at a suitable speed, and a simple mechanism for rotating the pitch disc is illustrated in FIG. 1 and comprises a motor **15** which drives a friction wheel **17** through a shaft **16**. The friction wheel **17** bears on a peripheral marginal portion of the pitch disc **8**. A bearing means is provided for the upper part of the spindle **13** in the form of a bearing holder **18** which supports a ball bearing assembly on an upward extension **19** of the spindle. The bearing holder **18** is mounted on an arm (not shown) pivotally attached to the side wall **10** of the housing at one end. A spring diagrammatically indicated at **20** extends between the housing **10** and the bearing holder **18** and spring biases the pitch disc **8** toward the friction wheel **17** to maintain engagement of the friction wheel and periphery of the pitch disc **8**.

FIG. 1 also illustrates a photocell assembly **26** disposed on the opposite side of the voice disc **9** from the pitch disc **8**. Various types of photocell assemblies may be utilized in the photoelectric organ here disclosed, such as those disclosed in the inventor's Pat. No. 3,249,678 en-

titled "Photoelectric Organ and Appurtenances," or those disclosed in the inventor's Pat. No. 3,023,657. Such photocell assemblies must in general be protected from external influences, such as the deleterious effects of atmospheric moisture and condensation. It may be preferable in some instances to provide separate covers for the photocell assemblies, but in the embodiment here set forth protection from atmospheric conditions is achieved by locating all of the photocell arrays **26** in a sealed chamber in which the voice disc **9** constitutes one wall. In FIG. 1, a base plate is shown at **21**, and the base plate is mounted on the structure described above by means of a series of posts **22** fastened on the side wall **10**. The upper plate **4** and the base plate **21** are fastened to these posts by screws, as shown. An O-ring **23** lies between the edge portions of the voice disc **9** and the base plate **21** so as to provide a peripheral seal. The O-ring **23** is made of elastomer material which is resilient and distortable, such as rubber or soft plastic. Since the housing for the lower bearing of the pitch disc spindle is normally held to the base plate by a screw **24**, it is advisable to apply an O-ring seal **25** between the structure **11** and the base plate **21**.

The above construction provides a sealed space in which the photocell arrays are housed and protected from moisture. The photocell array **26** is supported on a frame or bracket **27** in the particular embodiment illustrated, and the bracket in turn is mounted on the plate **21** by any suitable means, such as the bolt **28**.

It is advisable because of changes in atmospheric pressure and the likelihood that the sealing means may not be perfect to provide a desiccant in connection with the sealed space located between the base plate **21** and the voice disc **9**. A screw top vessel **29** is attached to the base plate **21** beneath an opening therein by means of threads **30** attached to the base plate **21** and a sealing ring **31**. The desiccant **32** may be of any suitable moisture absorbent material, e.g. silica gel, anhydrous calcium sulfate, or the like.

It is also advisable to provide a pressure equalizing means for the sealed space between the voice disc **9** and the base plate **21**. In the particular embodiment described, this is accomplished by means of an elongated capillary tube **33** passing in gas tight relationship through a fitting **34** in a perforation in the base plate **21**. The inside end of the capillary tube is bent at **35** to enter the container **29**. Other pressure equalizing systems, such as a bellows structure, may also be employed.

If photocell arrays are employed in which the cells are individually sealed, it is unnecessary to provide a sealed space between the base plate **21** and the voice disc **9**, or to provide means for desiccation and breathing. The base plate **21** may, in that event, be perforated, or simply a spider for supporting the photocell arrays **26**.

FIG. 2 diagrammatically illustrates the transparent areas **36** of the pitch disc **8**, the reference numeral **36A** being used to indicate a layer of opaque material, such as a photographic film, and the areas **36** are transparent regions in the layer **36A**. The layer **36A** is disposed on the surface of a glass plate **36B** which confronts the voice disc **9**. These layers are shown in exaggerated fashion in FIG. 1. FIG. 5 illustrates the transparent areas **36** in the form of slots with a rectangular configuration, and this is the form of the transparent areas **36** of the disc **8** in the particular embodiment of the invention described herein, as will be apparent hereinafter. The transparent areas **36** are arranged in a circular track, designated **36C**, which is disposed coaxially about the center of the pitch disc **8**, and the transparent areas **36** are spaced from each other as indicated in FIG. 5. Actually the transparent areas **36** may be quite narrow and quite closely spaced so that it becomes possible to include tracks for the desired frequencies throughout the entire range of the musical instrument upon a single pitch disc **8**, the disc **8** having a relatively small diameter of the order of one foot. Further, more than one tone generator of the type shown in FIG. 1 may be incorporated in a single electrical musical instrument.

The voice plate **9** also is constructed of a plate of transparent material, such as glass, designated **37A**, and the plate has on its surface confronting the pitch disc **8** a coating **37B** of opaque material, such as a photographic film. Various voice bands in the form of transparent or semi-transparent sectors diagrammatically illustrated at **37** in FIG. 2 are provided in the opaque film **37B**, and one of these transparent sectors for the particular organ illustrated is shown in FIG. 5. The transparent sectors **37** are centered coaxially with the track **36C** and have the same radius as the track **36C** so that rotation of the pitch disc **8** causes successive transparent areas **36** of the track **36C** to traverse the transparent sectors of the voice plate **9**. It has been found preferable to provide a plurality of voicing bands on the voicing plate **9** for each track of the pitch disc **8**. A photocell assembly **26** confronts each of the transparent sectors of the voicing plate **9** as will be more fully described hereinafter.

The pitch disc **8** and voicing plate **9** may be made photographically by processes and apparatus such as that illustrated in the patent to the present inventor, No. 2,839,960, issued June 24, 1958. Master copies of the pitch disc **8** and voicing plate **9** may be used for photographic reproduction of additional pitch discs **8** and voicing plates **9**.

The electrical musical instrument is provided with frequency vibrato by varying at a sub-audio rate the rotational speed of the pitch disc **8**. While this may be accomplished in a number of ways, FIG. 1 diagrammatically illustrates an armature member **38** attached to the pitch disc **8** for this purpose. A permanent magnet **39** is mounted at one end of a pivotally mounted arm **39A**, and the magnet is translatable relative to the armature member **38**. The armature **38** is provided with equally spaced outwardly extending teeth **38A** disposed in a cylindrical configuration. When the permanent magnet **39** is translated by movement of the arm **39A** to become disposed between the teeth **38A** of the armature **38**, the armature **38** will be periodically slowed by the magnetic attraction between the teeth **38A** and the magnet **39**, thus periodically slowing the pitch disc **8** and producing pitch vibrato.

The photocell assemblies **26** each contain a plurality of individual photocells. For simplicity, it is desirable that each photocell assembly **26** contains that number of photocells which will equal the number of semi-tones within the range of the instrument which is desired to be reproduced in connection with the particular voice with which that photocell assembly is utilized. Some voices extend through the entire range of the musical instrument, and in the usual case **61** photocells are required to produce all of the semi-tones of such a voice. For such a construction, **61** separate photocells may be employed in a single photocell assembly **26**, or more than one photocell assembly may be utilized to provide a photocell for each semi-tone of that voice. The photocells of each photocell assembly **26** are generally disposed in a straight line and equally spaced from each other, and the axis of the photocells is disposed upon a radius of the pitch disc **8** with one photocell confronting each track of the pitch disc **8**. Further, the voice plate **9** contains a transparent sector **37** aligned between each photocell and one of the tracks **36C** of the pitch disc **8**. It is desirable that space on the pitch disc **8** and voice plate **9** be conserved, and hence, the tracks **36C** of the pitch disc **8** are disposed as close to each other as practical. In practice, adjacent tracks of the pitch disc **8** may be spaced by distances of approximately $\frac{1}{16}$ inch between centers without providing cross talk between the desired photocell and the adjacent photocells on either side of the desired photocell. Hence, the photocell assemblies **26** may be quite

small, for example, approximately ¾ inch to 1 inch in width and approximately 4 inches in length.

The construction of the photocell assemblies **26** is shown in greater detail in FIGS. 3 and 4. The photocells themselves are disposed on a substrate or base **40** which is generally constructed of glass, although ceramics and other insulating substances may also be used. The photocell assembly employs two common electrodes **41** and **42** having interdigitating branches **43** and **44**. Between each pair of these interdigitating branches there is disposed a third electrode **45**. The common electrodes have terminal areas **46** and **47**, respectively, with which contact may be made, and there are enlarged regions **48** for contacting purposes on the ends of the third electrode **45** for contacting purposes.

Each photocell within the photocell assembly **26** comprises a first electrode which is part of one of the common electrode structures, a second or intermediate electrode, and a third electrode which is a branch of the other common electrode structure. The branches of the common electrode structures thus serve as electrodes for adjacent photocells. A strip or coating **49** of photosensitive material is disposed over the electrodes. The individual photocells in the photocell assembly **26** are made operative by electrical polarization, as described in the copending application of Clifford B. Luebbe, Ser. No. 127,236, filed July 27, 1961, and entitled "Photoelectric Structures."

FIG. 3 illustrates the photocell assembly **26** provided with a cover glass **50** secured thereon by a layer of electrically insulating cement **51**. The cover glass **50** must cover the strip **49** of photosensitive material, but leave exposed the contact areas **46**, **47** and **48**, and hence, the effectiveness of the cover glass **50** depends upon an airtight seal by the cement layer **51**.

FIGS. 3 and 4 illustrate a structure employing clip-like elements **52** for providing electrical contact to the contact areas **46**, **47** and **48**. These elements **52** are preferably double wire elements, as shown in FIG. 4, for the sake of positiveness of contact. Several clips are fastened in properly spaced relationship to insulating supports at **53**, and the clips are so shaped that one end will engage a contact element of an electrode, while soldered flexible wire connections may be made to the other end of the clip, i.e., at the point **54**. A clip-like element **52** is provided for each lateral edge of the photocell assembly **26**. Each clip element contains one or more clips for making contact with the common electrode structure and a plurality of clips for making individual contact with the conducting areas **48** of the intermediate electrodes. With this construction it is readily possible to remove and replace a photocell assembly **26** by slipping the lateral clips on each side off the edge of the old photocell assembly and on to the edges of a replaced photocell assembly.

The particular photocell assemblies illustrated in the figures are mounted by means of a mounting bar **27** which may be adhesively secured to the substrate or base **40** of the photocell assembly and held to the plate **21** by a rivet bolt **28**.

As is indicated in FIG. 2, the pitch disc **8** contains a plurality of tracks **36C** of transparent areas separated by opaque areas. The voice plate **9** contains sectors of voicing indicia **37** disposed in alignment with the tracks **36C** of the pitch disc **8**. Three photocell assemblies designated **101**, **102** and **103** are mounted on the base plate **21** of the housing **3**, and these bear the legends "flute," "diapason," and "oboe" to indicate that they pertain to different voices in the instrument. For purposes of polarizing the individual photocells of the photocell assemblies **26** and rendering them active, a circuit is shown comprising a source of direct potential **104** connected between the common ground return **105** and a bus **106**. Key switches are shown at **107**, **108**, **109**, and **110**, and each of these key switches has a connection to the bus **106** and another connection to leads **111**, **112**, **113**, and **114**, respectively, through transient reducing resistors **115**, **116**, **117**, and **118**. Each of these circuits is also provided with a transient reducing or tone envelope controlling means, comprising a capacitor and a resistor, these circuits being designated **119**, **120**, **121**, and **122**. The transient reducing circuits are also connected to the common ground return at **123**. It will be understood that the playing key switches are operated individually by the keys of the instrument.

The leads **111**, **112**, **113**, and **114** extend through a separable plug-in connector **124** for convenience in assembling the musical instrument. The circuit leads **111**, **112**, **113**, and **114** have branches extending to a plurality of the several photocell assemblies. Thus the lead **111** has a branch **125** extending to one of the intermediate electrodes in the photocell assembly **103**, a branch **126** extending to one of the intermediate electrodes in the photocell assembly **102**, and a branch **127** extending to one of the intermediate electrodes of the photocell assembly **101**.

The common electrodes of each photocell assembly are connected to stop tab switching means in order to permit the several voices of the instrument to be selected. Thus, the photocell assembly **101** has a lead **128** and a lead **129** connected to a stop tab switching means marked "flute tab." Similarly, the photocell assembly **102** is shown connected to a "diapason tab," as indicated. The common electrodes of the photocell assembly **103** have leads **130** and **131** connected to an "oboe tab." The switching arrangements of the several stop tabs are in turn connected with an output system comprising an amplifier **132** and a loudspeaker **133** to a transformer **134**. The transformer has a center-tapped primary winding, the center tap of which is grounded at **135**. The leads from the common electrodes of each photocell assembly **101**, **102**, and **103** are connected by the stop tab switching arrangements to points near the opposite ends of the primary winding of the transformer **134**.

It will be noted that a plurality of transparent sectors **37** are employed on the voice plate **9** confronting each track **36C** of the pitch disc, but each of the sectors **37** confronts a separate photocell in each photocell assembly. Further, the innermost transparent sector **37** is 180° out of phase with the outermost transparent sector **37** confronting the same track of the pitch disc **8**, thereby cancelling out the direct current component of the photocell signal impressed upon the transformer **134**, and only the audio signal is passed through the transformer to the amplifier **132**. When a second voice or additional voices are added while playing an organ, such as that described, the respective stop tabs of the voices are actuated and a transient is likely to occur. In order to avoid such transients, means are provided in association with the stop tab switching mechanism for eliminating this transient. In FIG. 2, the switching arrangement of the "oboe tab" is shown in the tab "off" position, and it may be noted that the lead **131** from the photocell assembly **103** is grounded through a switch component **136**. Likewise, the lead **130** from the photocell assembly **103** is grounded through a switch component **137**. The switches **136** and **137** are closed when the stop tab is in the "off" position, and are opened by moving the tab to the "on" position. The switches **136** and **137** are closed when the stop tab is in the "off" position, and are opened by moving the tab to the "on" position. Feedthrough of direct current bias to the photocell assembly not being played is thus eliminated. There are a pair of switch elements **138** and **139** in the "oboe tab" switching mechanism for connecting the lead **131** to a point to one side of the center tap of the primary winding of the transformer **134**. Similarly, there are a pair of switch elements **140** and **141** connected to the lead **130** for connecting this lead to a point on the other side of the center tab of the transformer primary. Closing the switch **138** completes this circuit through a resistor **142**, while closing the switch **140** completes the other circuit through a resistor **143**.

The mechanical actuation mechanism for the several

switch elements of the stop tab closes the switches **138** and **140** before closing the other switches of the stop tab when the tab is actuated. In this manner, electrical connection between the leads **130** and **131** to the primary winding of the transformer is first completed through the resistors **142** and **143** in order to prevent short circuiting of the primary of the transformer, since the photocell assembly is still grounded. Thereafter, the switch actuation mechanism opens switch **136**, allowing the photocell assembly current to flow equally in the two parts of the transformer winding, eliminating or minimizing the transient which might otherwise be produced. Thereafter, the switch **137** is opened allowing the audio current to flow in the transformer. Finally, the switches **139** and **141** close establishing a direct connection between the leads **130** and **131** and the primary of the transformer **134**. The switch elements of the flute tab and the diapason tab are shown in the positions they occupy when these tabs are in the "on" position.

When an electric organ constructed in the manner of FIGS. 1 through 4 is to be played, the pitch disc **8** is first placed in rotation at a constant rate by actuation of the motor **15**. The rotation rate of the pitch disc **8** should be as constant as possible unless the vibrato producing magnet **39** has been translated into the vibrato position to produce periodic speed variations in the pitch disc **8**, and even when operated in this manner, the average rotation rate of the pitch disc **8** should be a constant. Light will continuously be reflected by the deflector **2** onto the pitch disc **8**, and each track **36C** of the pitch disc will produce a beam of light for each of the slots or transparent openings **36**, and all of the beams of light thus produced rotate about the axis of the pitch disc and periodically impinge upon each of the photocell assemblies **101**, **102**, and **103**. Because of the shape of the slots **36**, each of the beams of light has a length longer than the width of the photocell, so that each beam of light extends across the entire width of the photocell. However, the width of each slot **36** is small compared to the length of the photocell, that is, the arc length of the photocell disposed normal to a radius of the pitch disc **8**, so that each beam of light covers only a relatively small portion of a photocell at a given time and in effect sweeps the photocell through a period of time due to rotation of the pitch disc **8**.

Merely producing an electrical signal from a photocell will not achieve the musical effect desired of a musical instrument, and the wave form produced from the photocell must be controlled to produce the desired musical tone. The wave patterns **37** modulate the amplitude of each beam of light impinging on a photocell as the photocell is scanned by that beam of light so that the electrical output from the photocell may rise and fall during a single cycle in response to the wave pattern **37** in order to produce an electrical signal representing a more desired musical tone.

The human ear readily differentiates differences in voicing between two tones of the same frequency, and the differences in voicing are primarily differences in the presence and amplitude of harmonics of the fundamental of the tone and side bands. FIG. 7A illustrates the relative amplitude which has been measured for the C♯5 diapason tone of a pipe organ. It will be noted that the fundamental frequency of the C♯5 dispason tone is 550 cycles per second illustrated by the sharp peak at **160**. FIG. 7A also illustrates the second harmonic **162**, the third harmonic **164**, the fourth harmonic **166**, and the fifth harmonic **168** of this tone, and it will be noted that these harmonics are of declining importance, the second harmonic being down approximately 10 decibels from the fundamental, the third harmonic being down approximately 20 decibels, the fourth harmonic being down approximately 35 decibels, and the fifth harmonic being down approximately 35 decibels. By proper selection of the shape of the wave pattern **37** of the voicing plate **9**, the amplitude of the light beams inpinging upon the photocell assembly can be modulated during each cycle to produce the harmonics of the fundamental of the desired frequency, and the amplitude of each of the harmonics may be also established. The wave patterns **37** of the tone plate **9** may be variable area patterns, as illustrated in FIG. 5, or the wave patterns **37** may be variable density patterns, since their function is to modulate the amplitude of the light impinging upon different portions of the photocell as the light beam sweeps the light sensitive center of the photocell.

The present invention is not limited to electrical musical instruments for imitating sounds produced by the pipes of a pipe organ, but the present invention will accomplish this end and is peculiarly adapted to accomplish this end in view of the somewhat random nature of the wave forms of pipe tones. It will be noted from FIG. 7A that the measured C♯5 diapason tone of a pipe organ contains significant side bands on both the upper side and lower side of the fundamental, the side bands on the upper side being designated **170**, and the side bands on the lower side being designated **172**. The tone produced by the electrical organ illustrated in FIGS. 1 through 5 cannot be made to simulate the upper side bands **170** and the lower side bands **172**, either of the fundamental frequency or the harmonics thereof, by simply shaping the wave pattern **37**, or in other words, modulating the beam of light impinging upon the photocells in a fixed and predetermined manner. It is necessary to add to the electrical signal produced by the photocells a low frequency modulation in order to produce side bands in the regions immediately adjacent to both sides of the fundamental frequency and the significant harmonics thereof.

Low frequency modulation of the electrical signal produced by the photocell is achieved by low frequency modulation of the light falling upon the photocell assemblies. As indicated in FIG. 7A, the most significant portion of the side bands occurs close to the fundamental frequency, and its harmonics. The modulation frequency should be very low. For example, for the C♯5 diapason organ tone, the most significant portion of the upper and lower side bands occurs within 34 cycles of the fundamental frequency for both the upper and lower side bands. Hence, the modulation frequency must be only a fraction of 34 cycles, the band of the significant portion of the side bands, if the side bands are to have substantial strength in this region. In other words, the fundamental of the side band modulation frequency and a plurality of harmonics of this frequency must all fall within the frequency band in which the predominant side bands occur, 34 cycles for the C♯5 diapason of the pipe organ.

In theelectric organ shown in FIGS. 1 through 5, side band modulation can be achieved by varying the width of the slots **37** in the pitch disc **8** and rotating the pitch disc **8** at a sufficiently low speed so that all significant harmonics of the side band modulation will fall within the range of predominant side bands. Since each slot will confront each photocell only once in each period of rotation of the pitch disc **8**, the fundamental side band modulation frequency will be that of the pitch disc **8**. In one particular embodiment of the electric organ illustrated in FIGS. 1 through 5, the pitch disc is rotated at a rate of 33.8 revolutions per minute, and hence has a frequency of 0.56 cycle per second. Each of the side bands appearing both above and below the fundamental of the tone produced, and each harmonic thereof, will thus be spaced by 0.56 cycle, and the higher harmonics of the side band modulation frequency will have greater attenuation than the lower harmonics of the side band modulation frequency.

It is thus apparent that the track **36C** of the pitch disc **8** has approximately 1000 slots in order to produce the C♯5 note. The lowest frequency normally used in an organ is 32.7 cycles per second. If this tone is produced by a pitch disc using 58 slots, the fundamental frequency of modulation is never more than $\frac{1}{58}$ of the tone frequency. Any fewer number of slots would mean a higher rotation rate of the pitch disc which would mean an

undesirable periodicity of the modulation produced by the side bands.

In FIG. 5, the slots **36** are indicated to have widths designated by the letter W, and these widths vary around the track **36C**. The greater the variation in widths W, the stronger will be the side band modulations. The variation in widths around the tone disc may be simply random, the amount of variation being selected to produce the desired magnitude of the side bands. Very pleasing voices may be produced by simply random variation of the widths W in the track **36C**.

The widths of the slots **36** may also be varied in accordance with a function, and the function may be determined from an existing musical tone in order to imitate that tone. In FIG. 6A, a function is shown which has been obtained by measuring the side band intensity of the C♯5 diapason of a pipe organ throughout a period equal to twice the period of the pitch disc **8**. Since the function shown in FIG. 6A is not a continuous function, that is, it cannot be placed upon a disc since it will not achieve proper re-entry, it is necessary to modify this function to achieve a continuous function. In FIG. 6(B) a tapered function for the same period is shown, the function being

$$\frac{1}{2}+\frac{1}{2}\cos \pi\frac{t}{T}$$

If the function of FIG. 6(A) is multiplied by the tapering function of FIG. 6(B), a tapered function is produced, such as shown in FIG. 6(C). By adding the first half of the function of FIG. 6(C) to the second half of the function of FIG. 6(C), the initial and ending values of a new function, shown in FIG. 6(D), will have the same values, and a continuous function will be produced which has the period of the pitch disc **8** and contains substantially the information measured from the C♯5 diapason tone of a pipe organ. The width of the slots **36** may be made to vary in accordance with the function of FIG. 6(D) around the track **36D** so that the light falling upon the photocell assemblies will vary in accordance with the function of FIG. 6(D).

It is to be recognized that the width of the slots **36** may be selected by simple mathematical means and provided manually. However, in an instrument constructed according to the specific embodiment herein set forth, it is difficult to provide approximately 1000 slots **36** of varying widths manually on a disc of approximately 1 foot diameter. It is preferable to utilize the function of FIG. 6(D) in the form of a mathematical equation which may be derived by Fourier analysis or curve fitting techniques. This equation may be used to control a computer for the production of magnetic tape for the control of a circle dividing machine. The inventor's Pat. No. 3,235,878 discloses the method and apparatus for producing pitch discs from a mathematical function.

It is to be noted from FIG. 7A that the upper side bands **170** are of greater significance than the lower side bands **172** of the C♯5 diapason tone of a pipe organ. One of the reasons for this fact is that the air pressure supplied to the pipe of a pipe organ is not a constant, and tends to frequency modulate the tone produced as well as amplitude modulate it. Another reason that the higher frequency side bands tend to predominate over the lower frequency side bands in a pipe organ tone is that the tone produced by the pipe is tuned to slightly below the natural resonance of the pipe, and hence noise generated by the pipe is in the higher frequency side band regions. Merely amplitude modulating the light source impinging upon the photocells of a photoelectric organ of the type shown in FIGS. 1 through 5 will not achieve a greater amplitude side band distribution on the high frequency side of the fundamental than on the low frequency side of the fundamental, and the harmonics thereon. This can be seen from FIG. 7B in which the solid lines **174** indicate side bands produced by amplitude modulation alone.

The side bands on one side of the fundamental frequency may be suppressed relative to the side bands on the other side of the fundamental frequency by adding frequency modulation correlated in phase with the amplitude modulation to the signals produced by the photocells. Frequency modulation can be achieved by varying the distance designated *d* between adjacent slots **36**, as indicated in FIG. 5.

The frequency modulation to be imparted to the resulting tone from the electric organ may be in accordance with a random function, as previously described in connection with the amplitude modulation, or it may be in accordance with a measured function of frequency modulation from a tone which is to be imitated. A tone of a pipe organ, such as the C♯5 diapason, may be analyzed for both frequency and amplitude modulation and separate functions, such as shown in FIG. 6(D) derived for the two types of modulations. In FIG. 7B the contribution of the frequency modulation alone to the upper and lower side band region of the C♯5 diapason produced by the electric organ according to the present invention is shown at **176**.

By combining the phase and amplitude modulation together in a particular phase relationship, any portion of the side bands on one side of the fundamental frequency, and harmonics thereof, may be suppressed to any desired degree, and FIG. 7C shows the manner in which the low frequency side bands **172** are suppressed relative to the high frequency side bands **170** in the organ of FIGS. 1 through 5, it additionally being noted that the shape of the envelope of the side bands in these regions also is varied in this process. If the frequency modulation is in phase with the amplitude modulation, and if each type of modulation produces the same amplitude of side bands, then the low frequency side bands are completely eliminated. If the phase angle between the amplitude modulation and the frequency modulation is about 45°, then both side bands are present, but differ by 7 decibels. In like manner, equal high frequency and low frequency side band regions are produced if the phase angle between the frequency modulation and amplitude modulation is 90°. If the frequency modulation is 180° out of phase with the amplitude modulation, and if each type of modulation produces the same amount of side bands, then the high frequency side bands are completely eliminated. It is thus clear that by selecting the phase angle between the frequency modulation and the amplitude modulation, the side bands within the regions immediately above and below the fundamental frequency and its harmonics may be shaped to simulate a desired voice.

Both the presence of frequency modulation and its phasal relation to amplitude modulation are determined by the centers of the slots **36** of the pitch disc **8**, and hence the distances designated *d*1, *d*2, *d*3, *d*4, and *dn* of FIG. 5 control these functions. It will be recognized that by control of the width of the slots **36** and their spacing, both frequency modulation and amplitude modulation are controlled, and the phasal relationship of the two modulations is established. Other mechanisms may also be utilized in an electric organ to provide amplitude modulation and phase modulation and to control the phase between these modulations.

It will be noted from FIGS. 2 and 5 that each wave patterns **37** covers three cycles. Hence, a given photocell produces an output which is the sum of the three signals generated as a result of three beams of light sweeping that photocell at the same time, one of the beams of light impinging upon each of the three cycles in the wave pattern. As a result of this construction, the electrical output of the photocell is enhanced and imperfections in the optical system are minimized.

Also as a result of the simultaneous sweeping of a plurality of cycles of the voice pattern **37** at the same

time, the pitch disc **8** must have its transparent sectors **36** of such widths that the electrical signal follows the function of FIG. 6(A) in the absence of a tone pattern **37**. The averaging of the illumination of three different portions of the same photocell limits the range of light modulation which can be achieved by varying the width of the slots and it permits a close tracing of the curve of FIG. 6(A) provided that the slope of the curve is not steep.

It has been found that amplitude modulation should not exceed 10 percent between peaks, that is, the width W of the slots of the pitch disc should not vary more than ±5 percent from the average width of the slots. In like manner, frequency modulation should not exceed ±0.1 percent from average center to center spacing of the slots.

Both frequency and amplitude modulation must be slow, that is, have a repetition rate no greater than one cycle per second. In addition, the modulation of the tracks **36C** of the pitch disc **8** should be as uncorrelated as possible to avoid amplitude or frequency modulation having an overall undesirable effect.

Those skilled in the art will devise other modes of practising the present invention other than that herein set forth. Further, those skilled in the art will devise applications for the present invention in addition to that set forth herein. It is therefore intened that the scope of the present invention be not limited by the foregoing disclosure, but rather only by the appended claims.

The invention claimed is:

1. An electrical musical instrument comprising, in combination: a tone generator for producing a plurality of audio frequency electrical signals, one of said electrical signals having the frequency of each tone to be generated; an electroacoustical transducer electrically coupled to the tone generator, a switch for each electrical signal for selection of those signals to be impressed on the transducer, and means operatively associated with the tone generator for amplitude modulating an audio frequency electrical signal at a repetition frequency less than 1/50 of the frequency of said audio frequency signal.

2. An electrical musical instrument comprising the combination of claim **1** wherein the tone generator includes a light source, a photocell, a scanner plate rotatably mounted between the light source and photocell, said scanner plate having a circular track disposed coaxially about the rotational axis of the plate having a portion disposed between the light source and the photocell, said track consisting of a plurality of transparent sectors spaced by opaque sectors, and the means for amplitude modulating the electrical signals comprising means for rotating the scanner plate at a constant average rate and said transparent sectors in the track are of different arc length about the track.

3. An electrical musical instrument comprising the combination of claim **1** in combination with means for frequency modulating an audio frequency electrical signal at a frequency less than 1/50 of the frequency of said audio frequency signal.

4. An electrical musical instrument comprising the combination of claim **2** wherein the center-to-center distance of the transparent sectors in the track are of different arc length about the track to produce frequency modulation.

5. An electrical musical instrument comprising the combination of claim **4** wherein the transparent sectors of the track with arc lengths longer than average are preceded by shorter than average center-to-center distance of the transparent sectors of the track to produce predominantly high frequency side bands.

6. An electrical musical instrument comprising, in combination: a support structure; a photocell mounted on the support structure having a light sensitive area extending along an axis; a light source mounted on the support structure confronting the light sensitive area of the photocell and producing an approximately equal light intensity over the sensitive area of the photocell; a voice plate mounted on the support structure between the photocell and the light source, said voice plate being opaque to light and having an elongated transparent region aligned with the axis of the sensitive region of the photocell, and said transparent region having different light transmission characteristics in different portions thereof disposed along the longitudinal axis of the transparent region; a pitch disc disposed between the light source and the photocell and mounted on the support structure for rotation about an axis, said pitch disc having a track coaxially disposed about the axis of rotation and aligned with the light source and light sensitive axis of the photocell consisting of a plurality of transparent sectors separated by opaque sectors, the transparent sectors having arc lengths short compared to the axis of light sensitivity of the photocell and the average spacing of the transparent sectors of the pitch disc measured between centers being less than the length of the axis of light sensitivity of the photocell; means mechanically coupled to the pitch disc for rotating the pitch disc at a constant average rate; characterized by the improved construction wherein the arc lengths of successive transparent sectors about the pitch disc differ according to the successive values of the dependent variable of a function for successive values of the independent variable from one to the number of transparent sectors in the track of the pitch disc, said function being non-linear and continuous and having fewer maximum values than 1/50 of the number of transparent areas in the track of the pitch disc, whereby the output of the photocell is amplitude modulated with the frequency of the pitch disc and multiples thereof, the magnitude of the amplitude modulation being determined within each period of rotation of the pitch disc by the instantaneous value of the function and the pattern of the amplitude modulation repeating for each period of rotation of the pitch disc.

7. An electrical musical instrument comprising the combination of claim **6** wherein the arc lengths between centers of adjacent transparent sectors about the track of the pitch disc differ according to successive values of the dependent variable of a second function for successive values of the independent variable from one to the number of opaque sectors in the track of the pitch disc, said function being non-linear and continuous and having fewer maximum values than 1/50 of the number of transparent areas in the track of the pitch disc, whereby the output of the photocell is also frequency modulated at the frequency of the pitch disc and multiples thereof, the magnitude of the frequency modulation being determined within each period of rotation of the pitch disc by the value of the function and the pattern of the frequency modulation repeating for each period of rotation of the pitch disc.

8. An electrical musical instrument comprising the combination of claim **6** wherein the function is substantially random.

9. An electrical musical instrument comprising the combination of claim **7** wherein the second function is substantially random.

10. An electrical musical instrument comprising the combination of claim **7** wherein the first function is out of phase with the second function.

11. A pitch disc for a photoelectric musical instrument comprising a flat disc having a rotational center and track disposed coaxially about the rotational center of the disc, said track having a plurality of transparent sectors spaced from each other by opaque sectors, characterized by the improved construction in which the transparent sectors have different arc lengths measured along the track, said arc lengths of the transparent sectors conforming to the values of the independent variable of a continuous non-linear mathematical function for the values of the dependent variable of said function from 1 to

the number of transparent sectors of the track, whereby said pitch disc may be rotated at a constant speed in a photoelectric tone generator of a musical instrument to produce a musical tone amplitude modulated at the frequency of rotation of the pitch disc at an amplitude determined by the mathematical function.

12. A pitch disc for a photoelectric musical instrument comprising the combination of claim **11** in which the center-to-center distance of transparent sectors of the track of the pitch disc have different arc lengths measured along the track, said arc lengths of said center-to-center distances conforming to the values of the independent variable of a second continuous non-linear mathematical function for the values of the dependent variable of said function from 1 to the number of opaque sectors of the track, whereby said pitch disc may be rotated at a constant speed in a photoelectric tone generator of a musical instrument to produce a musical tone amplitude and frequency modulated at the rotation rate of the pitch disc at amplitudes determined by the first and second mathematical functions respectively.

13. A pitch disc for a photoelectric musical instrument comprising the combination of claim **12** wherein the first and second mathematical functions have a positive correlation and are recorded on the pitch disc out of phase with each other.

14. A pitch disc for a photoelectric musical instrument comprising the combination of claim **11** wherein the first and second mathematical functions are essentially random.

15. A pitch disc for a photoelectric musical instrument comprising the combination of claim **12** wherein a plurality of additional tracks are disposed on the pitch disc coaxially about the rotational center thereof, each of said tracks having a different number of transparent sectors from the first track separated by opaque sectors, and each of said additional tracks being adapted to generate a musical tone of a different frequency when employed in the tone generator of a photoelectric organ.

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