Electronic Music*

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The following paper is one of a planned series of invited papers, in which men of recognized standing will review recent developments in, and the present status of, various fields in which noteworthy progress has been made.—*The Editor*

Summary—**The three attributes of musical sound, pitch, loudness and timbre, are discussed in relation to their counterparts in an electrical signal, frequency, amplitude and harmonic spectrum. Although electrical devices can control these quantities simply according to the explicit instructions contained in written music, that is, to provide the "bare essentials" of a musical performance, it is more difficult to produce the complex patterns of frequency, amplitude and harmonic spectrum actually found in a musical performance on well known instruments. Control of the build up and decay of each note, arbitrary deviations of pitch, vibrato of varying rates and amounts, and a "choir effect" of random pattern of beats are required. Various means of achieving these effects are discussed, first in the electronic organ and then in various "monophonic" or single-note instruments. Finally, coded-performance of "synthetic music" devices are described, including those used by the Musique Concrète Group of Paris, and the Cologne Studio for Electronic Music.**

Introduction

WHEN AN electronic engineer looks at music with a view to designing an electronic musical instrument, many things about music strike him as extremely fortunate. The music with which we are familiar may be represented to a good approximation by describing three attributes of the auditory sensation which vary with time: pitch, loudness, and timbre. Each of these variables has a counterpart which is well known in electronics, apart from sound. *Pitch* corresponds to frequency, a property of periodic phenomena; *loudness* to the amplitude of electrical oscillations, and *timbre* to the harmonic spectrum obtained by Fourier analysis. Methods of measuring and controlling frequency, amplitude, and harmonic spectrum are well known.

To begin with, a "musical" sound is usually thought of as a purely periodic one. The sound made by a card held against the teeth of a circular saw while it is being rotated produces a less musical sound than a siren, because in the first case the sound-producing process is less capable of exact repetition from one cycle to the next, than in the case of the second. Electrical generators are capable of giving much more exactly periodic sound than the mechanical generators commonly used in musical instruments, where variations in the surface of the bow, or turbulence in the air in front of the mouthpiece, cause differences between one cycle and the next which can be detected readily by the ear.

The musical scale seems to have been laid out especially for the benefit of the engineer. An octave represents a ratio of exactly 2:1, and the musical pitch scale is logarithmic, as nearly as the musician can tell us, in spite of the relatively large change of several semitones in the pitch (subjective) of pure tones with intensity.[1]

The timbre of a musical sound depends to a good approximation on the amplitude of the harmonics, and not upon their phase. Thus it is easier to synthesize a tone with a given timbre than a wave with a given waveform. Consonance, an offshoot of which is harmony, which is very important in our musical system, depends fundamentally upon agreement in the harmonics of the notes which are sounded together. The integral relations found among harmonics in an harmonic series underlie the frequency relations which determine consonance and frequency ratios found in chords and scales.

Although the accuracy to which frequency must be controlled for musical purposes is rather high—nearly one part in a thousand—electrical generators are for the most part more inherently stable than the mechanical ones used in conventional musical instruments.

The response of the ear to changes in sound intensity resulting from changes in amplitude of electrical oscillations is somewhat complicated, but on the other hand, a rather small number of steps—perhaps about ten—are sufficient to describe the variations encountered in the playing range of most musical instruments. Then, compared to electrical attenuators, the means which are used to control the loudness of the sounds in conventional musical instruments are horrifying, to say the least. In the pipe organ, to get a mere 25 decibels or so change in loudness, many ranks of pipes have been enclosed in brick-lined swell-boxes, provided with hollow, evacuated, aluminum shutters. The violinist spends years perfecting the technique of manipulating the bow in such a way that a pleasant sound will be elicited over a moderate dynamic range; the simplest electrical attenuators change sound intensity without disturbing periodicity and other characteristics of the sound.

The history of the progress of electrical music shows one after another of these fortunate relations between music and electronics being made the basis of a new

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[1] S. S. Stevens, "The relation of pitch to intensity," *J. Acoust. Soc. Amer.*, vol. 6, pp. 150–154; January, 1935.

musical instrument. Cahill, who in 1895 drew up the first comprehensive scheme for a completely electrical instrument,[2] made use of the integral relations between the various members of the harmonic series by generating all harmonics for one tone with alternators having a common shaft. Although to control loudness he used a vast number of power relays and rheostats controlling many hundred watts, his auditors were amazed at the ease of control of loudness which this apparatus afforded the performer, when compared with conventional instruments. Musicians were impressed by the stability of the tuning; in spite of the fact that when the first public demonstrations were made, the "Telechron" was some twenty years in the future, and means for controlling the frequency of alternators were comparatively undeveloped. In spite of the amplitude distortion which must have occurred in the telephone receivers which he used as loudspeakers, musicians praised the extreme "purity" of the tone.

Some thirty years elapsed before it was suspected that electrical tone might be too pure for musical purposes. The musical value of the ever-changing pattern of beats formed in pipe organ music by the inability of the pipes to stay in tune was not realized until technical knowledge had advanced to the point where instruments capable of staying mathematically in tune could be built, and until these instruments had been studied in a musical setting. Similarly, our present understanding of the musical significance of small changes in pitch, loudness, and timbre produced by the performer on a monophonic instrument was not attained until many instruments providing oversimplified control had been designed, built, and used beside older standard instruments. These subjects will be discussed later.

The first of the modern oscillators was perhaps Duddell's negative resistance oscillator, and he duly noted in his paper of 1900[3] the musical possibilities inherent in an oscillator with an entirely new and flexible method of controlling pitch.[4] After World War I, when vacuum tubes were well established, the heterodyne oscillator provided an even more spectacularly simple and flexible pitch control, which became the basis of the "Theremin," an aggressively futuristic instrument, and the "Ondes Martenot," which was heard in a program of the Boston Symphony Orchestra a few years ago. A glance at the pitch-changing mechanisms of the double-bass and the pedal clarinet shows why electronic oscillators provoked so much interest.

In the "Thirties," after the cone speaker and ac-operated tubes had prepared the way for reliable sound-producing equipment, all the known types of mechanical and electronic oscillators were tried as generators in electrical musical instruments. The review of the generator question at that time was so thorough that no new generators have since been discovered, although the marked improvement in the performance of electronic components has been responsible for an increasing preference for electronic generators, rather than mechanical ones. A great variety of monophonic instruments had been experimented on in the "Twenties" and some had actually reached the stage of being manufactured. However, commercial success was first achieved by the electronic organ, which has increased steadily in economic importance.

The Electronic Organ

The commercial success of the electronic organ is based on the fact that while the individual generators are more expensive on the average than the individual pipes in the pipe organ, each electrical generator may be made to take the place of a number of pipes. Organ builders have had little success in using the same pipes to provide different sound intensities, although a single pipe has been used to sound at different ptiches.[5] An electrical generator might, however, appear on an electronic organ as a "diapason," and the same generator, with its voltage attenuated, might be heard as a "dulciana." With a little more elaboration of circuitry, the generator might be made to do duty for a number of different pipes by using appropriate electrical networks to modify the harmonic structure. Cahill had pointed out that the number of generators required to synthesize an harmonic series for each note in the musical scale could be reduced by taking account of the integral ratio required for consonant intervals which occur in the scale. In the Hammond Organ[6] some ninety generators are used to provide fundamentals and harmonics for nearly as many notes in the musical scale. Individual control of amplitude of each harmonic is provided in a way impossible in an acoustic instrument.

Timbre

The hope of early experimenters that electronic instruments would provide organists with completely new timbres of great beauty has not been realized. In the first place, the ability of the ear to recognize variations in harmonic structures, and thus the number of distinguishable timbres, has been greatly over-rated. We have all noticed that musical instruments can be recognized when heard under circumstances which alter harmonic spectra by an amount which greatly exceeds difference between the spectra of the musical instruments. An interesting lecture demonstration by K. A. MacFadyen[7] shows it is difficult to distinguish between

[2] T. Cahill, U. S. Patent 520,667, applied for in 1895.

[3] W. Duddell, "On rapid variations in the current through the direct-current arc," *J. Inst. Elec. Eng.*, vol. 30, pp. 232–267; 1900–1901.

[4] Negative resistance oscillators were to become very popular with electronic instrument designers. An observer in the early "Thirties" noted that performers on the "Trautonium" carried about with them, and carefully protected, their pet neon lamps, much as a clarinettist does his pet reed.

[5] The "Polyphone," manufactured by the John Compton Organ Co., is a single pipe, tuned by pneumatic motors to cover the lowest octave of a 32-foot pedal stop. It has been found satisfactory to sound the four lowest notes, C to E♭, at E♭ pitch (19.65 cps), since at this pitch a listener cannot detect the difference between the pitch sounded and the true pitch.

[6] L. Hammond, U. S. Patent 1,956,350, applied for in 1934.

[7] K. A. MacFadyen, "Acoustical measurements and the organ" (parts I and II), *The Organ*, vol. 34, pp. 155–162; January, 1955, and pp. 200–203; April, 1955.

the steady-state sound of the trumpet and flute under circumstances where inclusion of the starting transient would leave no doubt whatever as to identity of the instrument. Anyone who has access to a tape recorder, a pair of scissors, and a few musical instruments, can do some interesting experiments on effect of starting period on instrument recognition. Attack and decay processes can be made to change places by reversing tape, and artificial starting periods, produced by cutting tape obliquely through the steady-state period, can be substituted for the natural ones.

In the second place, harmonic synthesis, that most thorough-going method of timbre control, is the peculiar property of the pipe organ. For many centuries individual harmonics up to the eighth have been available as mutation and foundation stops. The sprightly fifth harmonic, heard in Ravel's "Bolero," was undoubtedly suggested by the corresponding mutation stop on the pipe organ sometimes referred to as the "tierce." All the harmonic distributions not found in natural spectra[8] have thus become familiar through pipe organ music.

Up to a point, each harmonic exerts a characteristic effect on timbre. The effect of the octave harmonics—the second, fourth, and eighth—is closely related. When the higher octave harmonics predominate, the "octave" effect is brighter than when the lower octave harmonics predominate. Nonoctave harmonics, such as the third and fifth, also have a related effect: they make tone more strident, assertive, and have effect of emphasizing the pitch of the fundamental; whereas octave harmonics tend to create a confusion in pitch between the fundamental and its octaves. High relative intensities of nonoctave harmonics tend to produce a timbre useful for solo work because of assertive quality and definite pitch, but not too satisfactory for playing chords because of the possibility of the prominent harmonic jumping out of the mixture and being classified by the ear as an independent dissonant note.

It is not surprising that the ear will accept inharmonic partials on almost the same basis as true harmonics, provided no unpleasant beating is set up with adjacent harmonics. The writer has used the 5.33th "harmonic" and the 6.66th "harmonic" in steady organ tones, for example. While in our music, purely periodic sounds are given preference, many accepted sounds such as given by tympani, for instance, have continuous distributions, while other sounds such as those of gongs and chimes have inharmonic partials. Unpleasant effect produced when tones containing many inharmonic partials are used to form chords may be due to high probability of unpleasant beating, but is more likely due to failure of ear to resolve the mixture into the right number of tones[9] having intended pitch.

The writer believes that too much emphasis has been placed on the "pleasant" nature of consonant intervals, whereas they would be better described as "recognizable." The steady progression over the years toward intervals of lower and lower consonance is thus seen as due to the increasing familiarity of composer and audience with the domain of pitch, and the ever-changing rules of harmony are seen as a working indication of how complicated a pattern a given audience can be expected to follow. Meyer-Eppler has stated that the essential nature of an interval is not a consequence of the pattern of beating (which depends upon whether a tone has harmonic or inharmonic partials), but is due to the special ability of the ear to recognize periodicity as a special property of sound phenomena.[10]

In connection with the phenomena of consonance, reference should be made to the very special nature of sound formed by harmonic synthesis from sine wave sources tuned to the equitempered scale—a fact which has received surprisingly little discussion in print. Above a certain point on the keyboard a classical discord is impossible, because the separation of adjacent generators in cycles per second is insufficient to cause a sensation of roughness. In the octave below this point only minor seconds could be disagreeable. While one observer[11] has found a characteristic harmoniousness in the sound, and described the use of tempered harmonics as a basic improvement, another[12] states that the tuning accuracy of sine wave generators for additive synthesis must be of the order of one part in 10,000 or better.

After Helmholtz' demonstration of the relation between harmonic spectrum and musical quality, or timbre,[13] it was assumed that the reason the various orchestral instruments are apprehended musically as very distinct entities was due to the fact that each instrument has a characteristic harmonic spectrum. This mistake was due largely to the difficulty of making harmonic analysis. Meyer and Buchmann[14] published in 1931 an extensive investigation of many musical instruments covering a wide range of frequencies. One of these for the oboe is shown in Fig. 1. These analyses, made with the now familiar heterodyne analyzer, showed that the harmonic spectrum of musical instruments varies widely from one end of the range to the other. Apparatus for taking sound spectrograms rapidly, sometimes known as visible speech apparatus, has recently extended the range of sound phenomena which can be studied conveniently by sound spectrograms.[15] Fig. 2 shows a spectrogram of a violin sound made on a new sound spectrograph developed recently at the Murray Hill Laboratory of the Bell Telephone Lab-

[8] It would, for example, be very difficult to produce in a musical instrument a spectrum in which the fifth harmonic was 20 db more intense than the fourth or sixth, except by synthesis.

[9] The effect of recognizing a chord played with bells or tubular chimes is predominantly one of surprise at having performed a difficult feat.

[10] W. Meyer-Eppler, "The mathematical-acoustical fundamentals of electrical sound composition," (see footnote 58).

[11] S. T. Fisher, "An engineer looks at music," *Engrg. Jour.*, vol. 25, pp. 548–553; October, 1942.

[12] A. Douglas, "The electrical synthesis of musical tones, part 3," *Electronic Engrg.*, vol. 25, pp. 370–373; September, 1953.

[13] The French word "timbre" means "stamp" or "character."

[14] E. Meyer and G. Buchmann, "Die klangspektren der musikinstrumente," *Verlag der Akademie der Wissenschaften*, vol. 32, pp. 3–45; December, 1931.

[15] R. K. Potter, G. A. Kopp, and H. C. Green, "Visible Speech," D. Van Nostrand Co., New York, N. Y., 1947.

oratories. A glide extending over a little less than an octave is followed by a steady tone to which vibrato is added gradually. The vibrato at the end is scarcely noticeable on the fundamental, but becomes more so in the higher harmonics because of the linear frequency scale. A separate spectrogram gives a frequency calibration. The time scale is about four inches per second.

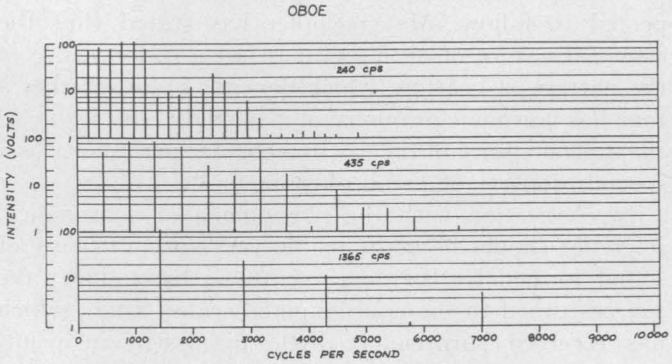

Fig. 1—Spectral analysis of three notes on the oboe obtained by Meyer and Buchmann, 1931. (After Meyer and Buchmann.)

When the spectra for tones of various pitch are looked at on the same frequency scale it is seen that there is a common element at work emphasizing certain frequencies no matter what the pitch of the note sounded may be. The frequency-selective elements are known as "formants." Trautwein[16] was the first to use in an electronic musical instrument an electrical analog for the formants which occur in mechanical musical instruments. Thus if there is a common quality among the timbres of the different tones emitted at different pitches by the same instrument, it may be due partly to the constancy of the formant position. The ability of the ear to recognize a certain pattern of formant behavior in sounds of widely-differing pitch is shown by the ease with which vowel sounds can be recognized whether sung by a bass voice or a soprano voice. At the same time, as anyone knows who has attempted to imitate orchestral instruments with electrical generators, the most distinctive characteristic of the clarinet is the suppression of the second and fourth harmonics, even though this occurs in the lower register only. Martin[17] points out how little the sound of a flute resembles a laboratory oscillator, even though the harmonic analysis of some flute tones reveals little but fundamental. We are led to conclude that the physics of "familiar" sounds is very complex.

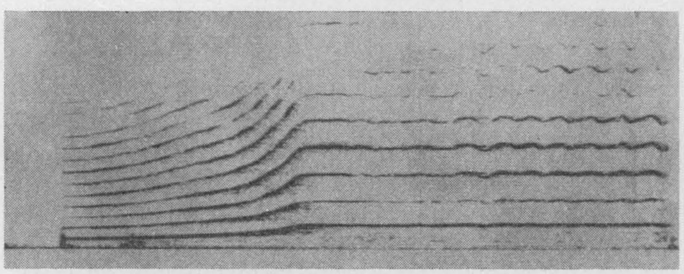

Fig. 2—Spectrogram of a violin sound made on a new spectrograph developed recently at the Murray Hill Lab. of the Bell Telephone Labs. (Spectrogram supplied through courtesy of the Acoustic Research Dept. Bell Telephone Labs.)

Towards the end of the "Thirties" it was realized[18] that the basic problem in designing timbre-control circuits was to find some means of providing a fairly-detailed control of the distinctive lower harmonics, such as the second, third, fourth, and fifth, while exerting only a modifying influence on a large group of harmonics extending up perhaps to the thirtieth. The difficulty with harmonic synthesis from sine waves is that if enough harmonics are provided, the system is too expensive and provides much more control over the higher harmonics than is required. The formant method, while providing an admirable solution for control of timbre on an electronic instrument patterned after the orchestral instruments, suffers from a limitation when applied to the design of the organ, due to the fact that the pipe organ covers a much greater range than orchestral instruments. An examination of the harmonic spectra of the pipes on the pipe organ which imitate orchestral instruments such as the oboe, shows the presence of a "variable formant," since the resonant structure is different for each pipe. The dependency of the spectrum of organ pipes on pitch is thus midway between the constancy with pitch obtained by harmonic synthesis and the extreme variation found in orchestral instruments. The consequence of this fact for electric organ designers is that formant circuits used over a whole manual must be restricted in their sharpness in order to keep the loudness all over the keyboard within acceptable limits.

While there is thus little hope of finding a practical way of imitating exactly orchestral or even pipe organ sounds, it seems reasonable to expect that the designer of electronic organs should be able to arrive at new solutions to the much more important problem of providing musically useful sounds. Harrison, in "The King of Instruments" series of records,[19] remarks that the test of a really musical sound is whether any note in the chord being held will be missed if dropped out, and heard reentering. An excellent demonstration is given on this record of the unsuitability of the "phonon diapason" (a pipe favored by romantic organ-builders) for polyphonic music. MacFadyen[7] has shown that on the basis of what is known about masking, a soft-toned stop—one having low harmonic development—must have an upward tilt in the loudness characteristics toward the top of the manual in order that the low notes will not make the high notes inaudible through masking. When the harmonic spectrum is more complex, he suggests it is possible to obtain the required clarity of tone with a constant loudness characteristic over the whole manual by emphasizing the higher harmonics of the low notes.

[16] F. Trautwein, "Elektrische Musik," Verlag Weidman, Berlin, Ger., 1930.
[17] D. W. Martin, "Thoughts on the imitation of natural sounds," *J. Acoust. Soc. Amer.*, vol. 25, p. 158; January, 1953.
[18] W. F. Curtis, U. S. Patent 2,227,068, applied for in 1939.
[19] "The American Classic Organ," Record I of "The King of Instruments," Aeolian-Skinner Organ Co., Boston, Mass.

The tendency in present-day electronic organ design seems to be to combine the three possible methods of varying timbre:

1) provide a number of basic waveforms for the same pitch,
2) modify the basic waveforms by electrical networks common to the whole manual, and
3) provide mutation stops derived from the main generators, plus as many octaves as possible.

In the Baldwin Organ, for instance, two different basic waveforms, the square-wave and the sawtooth, are obtained from electronic dividers. Formant circuits operating on these two basic waveforms provide a wide variety of timbres which are available in a number of registers.[20] The Robb Wave Organ, which was manufactured in Canada during the "Thirties," used a number of basic waveforms which were combined in various proportions to form the timbre resources of the instrument. The basic waveforms were generated by rotating steel cylinders carrying milled contours in front of the magnetic pick-up coils. The twelve cylinders may be seen in Fig. 3. The stators carrying the pick-up coils may be seen in the front row, while in the back row, the steel cylinders carrying the contours are visible in front of the stators.

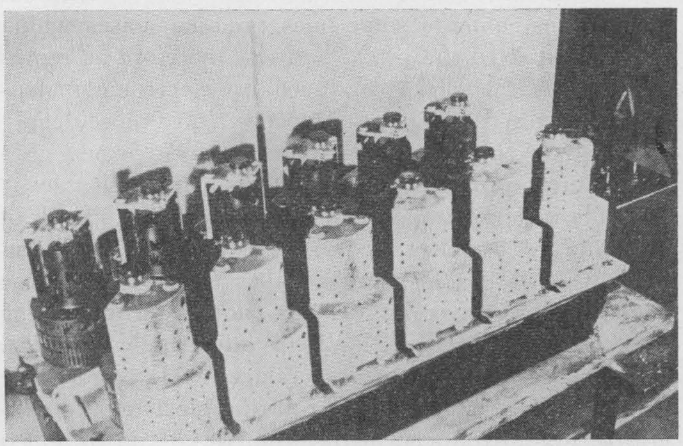

Fig. 3—The generators of the Robb Wave Organ, an electronic organ manufactured in Canada in the "Thirties." (Photograph courtesy of Morse Robb, Montreal, Can.)

In the Compton "Electrone" a number of basic waveforms, each having an harmonic spectrum representative of a class of organ tone, are engraved upon a disc which forms the stator of an electrostatic generator.[21] Fig. 4(a) is a photograph of the disc which carries these waveforms. The waveforms are scanned by a rotor shown in Fig. 4(b). In this design it is economically feasible to provide a variety of attacks.

Speech, Clicks, and Attack

Electronic organs differ from pipe organs in the manner in which the tones start and stop. The ear is conditioned to pay much more attention to the former than to the latter, since the rhythms in music depend almost entirely on the starting of the tones. The essential character of a melody is the same, played either staccato or legato. The cessation of a tone is, moreover, usually disguised by room reverberation. Thus the decay of a note attracts the listener's attention only if it is very rapid and begins as soon as the note has reached peak intensity, as with some percussion instruments.

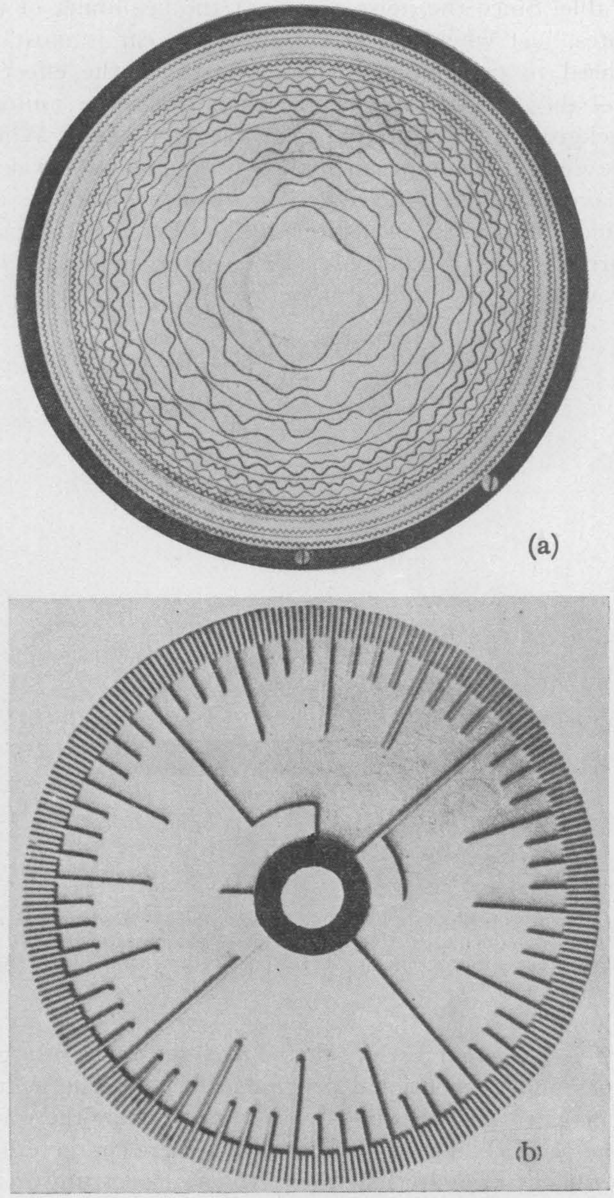

Fig. 4—(a) Stator of an electrostatic generator in the John Compton Organ Co.'s "Electrone"; the waveforms are engraved upon a metallised insulating disc, (b) Rotor of the electrostatic generator. (Photographs courtesy of the John Compton Organ Co., London, Eng.)

It is characteristic of electronic methods of tone formation that very rapid changes in intensity or frequency are possible, and may indeed be troublesome to avoid. A simple tone which is suddenly initiated at time $T=0$, then continues for something like a tenth of a second with undiminished intensity, is shown in Fig. 5(a). Although the manner in which the tone is produced

[20] R. H. Dorf, "Electronic Musical Instruments," Audio Library No. 1, Radio Magazines Inc., Mineola, N. Y., pp. 46–49, 1954.
[21] *Ibid.*, pp. 173–177.

suggests the spectrogram shown in Fig. 5(b), it nevertheless has the spectrum shown in Fig. 5(c). The sudden start and stop of the oscillation brings about a considerable widening in the time-frequency spectrum, which can be heard as a "click." The ear requires a minimum of about 13 milliseconds (depending upon the frequency) to recognize a sound as having a definite pitch. The effect of the broadening of the spectrum, shown in Fig. 5, is to distract the attention from the pitch of the notes being played, and is therefore undesirable. Since the noise occurs at the beginning of the notes, just when the attention of the ear is most required to perceive the melodic pattern, the effect is probably considerably worse than that of a uniform background noise of the same average energy. Where the design of the organ makes a rectangular envelope unavoidable, a noticeable improvement may be obtained by the use of a filter, if the filter is sufficiently narrow. For this purpose, a recent organ design has provided filters grouped in octaves.[22]

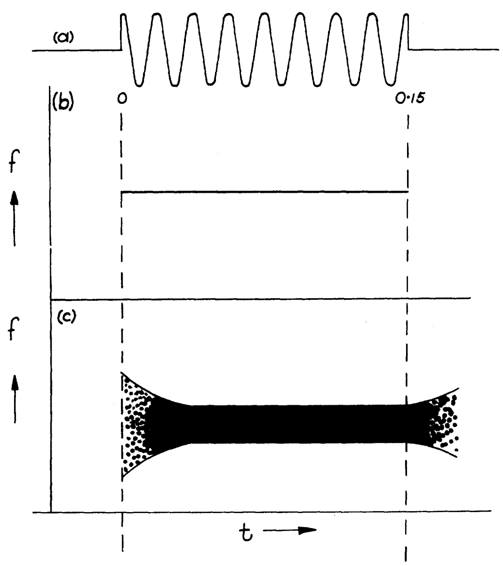

Fig. 5—(a) Oscillogram of a short sinusoidal tone, stopped and started suddenly, (b) Representation of the physical process and apparent spectrogram, (c) True spectrogram (simplified). (After Meyer-Eppler.)

There is great variety in the way the tones of organ pipes and conventional instruments start. The lecture demonstration mentioned earlier[7] shows that the way a tone begins in a trumpet or a flute is more characteristic of the instrument than the harmonic spectrum of the steady-state tone. When the build-up is very rapid, the effect of the build-up on the listener is welded very closely to the other attributes of the tone. It is, in fact, often confused with timbre. If the build-up time is much faster than one-hundredth of a second, the listener begins to perceive the enlargement of the spectrum as a "click." If the build-up time is much slower than one-tenth of a second, the listener perceives a tone steadily increasing in loudness. There is usually a significant change in harmonic spectrum during the build-up of the tone. There is sometimes a characteristic waver in pitch, or a frequency modulation by noise voltage, which is especially prominent during build-up. Sometimes narrow-band noise is present during the build-up, in strengths comparable in intensity to the musical part of the tone. All the foregoing factors determine the "speech" of an organ pipe or a musical instrument. They play a very important part in giving character to the instrument and in making its voice recognizable when heard with other voices in an ensemble. Although marked idiosyncracies of speech give a pipe the pronounced individuality required for solo work, they do not help it to satisfy Harrison's definition, given above, of a musical sound suitable for use in polyphonic organ music, since the peculiarities of speech do not prevent the tone being lost when sustained in an inner part. Thus polyphonic organ music is not always successful when played on the harpsichord, for example, which underlines the entrance of every new note so forcefully that a sustained note is lost long before the intensity has decayed appreciably. In addition to the processes which are closely connected to the pitch of a note, and are therefore useful in drawing attention to a new tone and giving it individuality, conventional musical instruments sometimes produce noises which are unrelated to the pitch, and are therefore as reprehensible as the clicks produced by electronic instruments having rectangular envelopes. Only those deeply attached to the piano in its present form would consider thump obtained on high notes a musical asset.

While it is not impossible to duplicate the speech of organ pipes by electronic means, the physical complexity of the organ sounds makes the apparatus too expensive. Some organ designs, notably those using electrostatic generators, however, allow the economical inclusion of several attacks. Bourne's electronic pipe organ auxiliary, based on a rotating electrostatic generator, was introduced in the "Thirties," and provided the performer with extensive envelope control, including many percussive effects.[23] The post-war version of this instrument is the Compton "Electrone"[21] which has been mentioned in an earlier section. Another approach to the problem of providing a variety of attacks is through the touch-sensitive action, which is discussed in a later section.

Choir Effect, Tremolo, and Vibrato

Although one of the advantages of electronic organs is the fact that one generator may do duty in many places, this economy results in a simplification of the sound texture due to the elimination of beats between mistuned generators. The true "choir effect" obtained

[22] G. H. Hadden, "Some considerations regarding volume production of electronic musical instruments," *J. Audio Engrg. Soc.*, vol. 1, pp. 29–36; January, 1953.

[23] "Electrical organ tones," editorial, *Wireless World*, vol. 36, pp. 514–515; May, 1935.

in a large pipe organ makes it possible for the full organ sound to be extremely bright without sounding "hard" or "screaming," and gives it instead a scintillating quality. The very satisfying feeling produced by the choir effect is undoubtedly connected with the inability of the ear to function properly under continuous stimulation.

The choir effect is vaguely related to the tremolo, an amplitude modulation at 5 or 6 cycles, and to the vibrato, a frequency modulation at 6 or 7 c. The universal adoption of intelligently applied vibrato has been responsible for a good deal of the improvement in the sound of the electronic organ which has taken place since the "Thirties." Thanks to the efforts of engineers during that period, we now hear rectangular envelopes disguised by synthetic reverberation, and the hard quality of sustained tones which is caused by their excessive purity—that is, constancy of frequency and amplitude of the electronic tones—is blurred by the application of vibrato. It is also interesting to recall how little the popular appeal of vibrato on organ tones was appreciated in the "Thirties." As far as the writer knows, Bourne's electronic pipe organ auxiliary[23] was the first commercially available organ to be provided with a true vibrato. When we recall how difficult it is to drive rotary equipment without periodic variations in driving speed, it is all the more surprising that the organs of the "Thirties" using rotating generators (with the one exception noted) did not provide vibrato effects.

Vibrato is a very effective device when correctly applied, the musical usefulness of which far exceeds the simple function of disguising the excessive purity of electronic tones. Vibrato is related to biological tremors, and when used by a player of an expressive instrument, is clearly connected with the fluctuations of the emotional temperature of the music. An extensive analysis of the vibrato has been made by Seashore[24,25] at the University of Iowa. A novel method for the production of vibrato based on the Doppler effect in an electrical line was patented by Hanert[26] in 1943, and is now used in the Hammond Organ.

A mechanical vibrato which is not under the direct control of the player—that is, which can only be turned "on" or "off"—while tolerable in background music, cannot be used more than a small percentage of the time in music which is to occupy the attention of a serious audience. The reason for the unmusical effect produced by prolonged use of a mechanical vibrato seems to lie in the fact that, unlike the choir effect which modifies the hard effect of pure tones without making the listener aware of a periodicity, the mechanical vibrato has a tyrannical and overriding effect which forces itself on the attention of the listener and breaks up the delicate and more rapidly moving patterns of the music. Although players of expressive instruments use vibrato a large part of the time, their vibrato is carefully related to the pattern of the music. The very mechanics of the application of vibrato to stringed instruments materially assists the player in this regard.

Unfortunately, to produce a successful choir effect, a high degree of complication and unpredictability is essential. The choir effect achieved by including just one extra set of generators is unsatisfactory, since after some minutes have elapsed the listener begins to perceive and then be distracted by the regularly recurring periodicities which are produced. The widespread use of electronic generators increases the complexity of the frequency and amplitude variations which may be introduced economically. The application of frequency modulation by a low-frequency noise source to the top oscillator of a divider chain can be carried out quite simply, and adds a pleasant "waver," but is useful to a rather limited degree in alleviating the "hardness" of tones of constant pitch and amplitude.

Several commercial instruments have provided an extra "vibrato" running at the beating rate to which the "unda maris" and "celeste" stops are usually tuned; that is, between one and two cps. When this is used together with the normal vibrato, an effect slightly suggestive of the choir effect is obtained. A novel musical effect was suggested by Hanert.[27] In this arrangement the beating rate between the auxiliary generators and the main generators varied from 6 to 8 c at 400 c, to 9 to 13 c at 2,400 c. The high beating rate at the low frequencies produced what was thought to be the maximum usable choir effect in bright tones.

Another arrangement suggested by Hanert[28] involves three oscillators for each note, each of which could be frequency modulated. Slightly different frequencies such as 5, 6, and 7 cps were used, the beat rates being thus confused.

The choir effect now used in the Hammond Organ, also due to Hanert[29] while not as musically satisfactory as the two just described, is much easier to manufacture in conjunction with the Doppler-effect vibrato.[26] In this scheme some of the unaltered signal is combined with the signal to which vibrato has been added. Addition of the unmodulated signal produces an amplitude modulation in addition to the phase modulation. The pattern of beats is complicated by the fact that the phase shift between the signals which are combined depends upon frequency, hence the nature of the amplitude modulation is different for each harmonic. Thus the periodicity is less obtrusive and less objectionable than in the case of a simple vibrato. Since for any note or harmonic the cycle repeats at the scanning frequency, the effect of a periodicity is by no means entirely absent, and the result is not as satisfactory as a true choir ef-

[24] C. E. Seashore, "The Vibrato," Studies in the Psychology of Music Series, vol. 1, The University of Iowa, Iowa City, Iowa; 1932.
[25] C. E. Seashore, "Psychology of the Vibrato in Voice and Instrument," Studies in the Psychology of Music Series, vol. 3, The University of Iowa, Iowa City, Iowa; 1936.
[26] J. M. Hanert, U. S. Patent, 2,382,413, applied for in 1943.
[27] J. M. Hanert, U. S. Patent 2,498,367, applied for in 1944.
[28] J. M. Hanert, U. S. Patent 2,500,820, applied for in 1945.
[29] J. M. Hanert, U. S. Patent 2,509,923, applied for in 1946.

fect. The problem of the electrical simulation of the choir effect obtained in a pipe organ is thus essentially an economic one, and an entirely satisfactory solution has not yet been obtained.

Reverberation

The writer believes that tones which end rather suddenly, even though no undesirable click can be noticed, are less useful in music than those which die away slowly, since the slow decay has little effect on the ease with which intricate and rapidly moving rhythms can be detected, and it assists the listener in fixing the pitch of the note. The most suitable decay time for well known music is probably that found for optimum reverberation time, that is, about 1.6 seconds. However this may be, the long reverberation which is characteristic of the structures in which pipe organs are usuallv heard, is felt to be an essential part of organ music. Builders of pipe organs have used special reverberant chambers with good effect when building conditions were unfavorable. Much ingenuity has been shown by designers of electric organs since the "Thirties" in providing synthetic reverberation effects which are suited to organ music.[30] In a recently developed type[31] reverberation coils of steel wire are coupled mechanically to a cone which is smaller than the loudspeaker cone and mounted concentrically in front of it. Vibrational energy absorbed by the reverberation coils is transmitted to the auxiliary cone and radiated as reverberant sound at a later time.

The Touch-Sensitive Organ

The electronic organ makes possible a touch-sensitive action which is virtually impossible with the pipe organ. The removal from the performer of intimate control of the loudness of the sound produced by the pipe organ is the result of its mechanical complexity. A glance at the structure of the most common types of music suggests that the loss of control of the loudness is a very serious one. The rapidity with which the piano replaced the harpsichord some 250 years ago confirms this impression. In fact, if we were unacquainted with the artistic excellence of preromantic organ music, it would be difficult to believe that a performer could produce effective music simply by timing accurately the entrance and exit of the sounds.

When considering a touch-sensitive action for the organ, one immediately wonders whether or not the organist could exert a satisfactory control over the loudness of each of the notes. The attention which the performer brings to bear over controlling the loudness is, of necessity, diverted from the control of the entrance and exit of the note, which therefore must become less precise. It also becomes possible for a performer to turn out a bad performance because some of the notes are incorrectly accented; whereas, with the standard organ, incorrect timing is the only possible fault. A similar comparison might be made between the piano and the harpsichord. In a piano transcription of harpsichord music, ornaments, and rapid runs lose some of the crispness and beautiful clarity which they would have on a harpsichord. It seems likely, however, that once the touch-sensitive keyboard has been mastered, the texture of contrapuntal passages and the independence of the parts will be considerably enhanced by the ability to accent certain notes slightly, and to obtain a crescendo or decrescendo of parts independently. The ability of the performer to control the attack and decay of each note independently gives rise to interesting possibilities for maintaining the independent character of parts. In imitating the stops of the baroque organ, a considerably more satisfactory effect is obtained with a given timbre when a touch-sensitive keyboard is used in place of the conventional kind. The direct control of the air valves used on baroque organs led to a certain degree of touch-sensitivity, although it was not very satisfactory.

The touch-sensitive issue may then be stated as follows: a fine structure in the loudness pattern and individuality of parts may be obtained with the touch-sensitive action, while the "expression" pedal is more suited to production of general fluctuations in loudness covering a wide dynamic range, and accompanied by the inevitable merging of the individual parts into the general mass of sound.

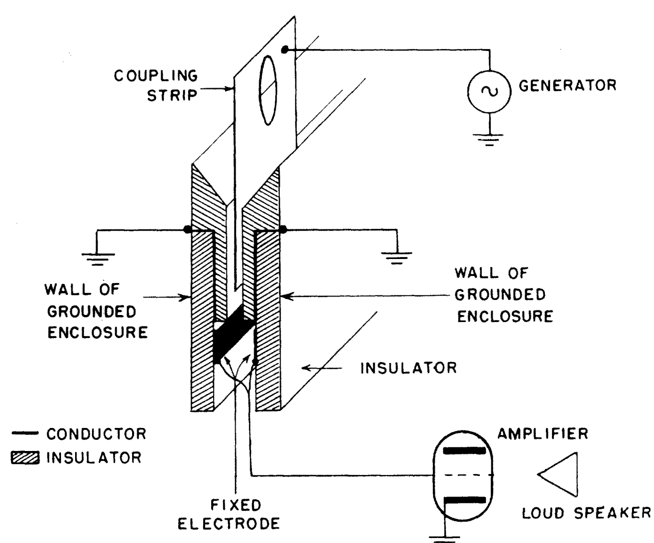

Fig. 6—Electrostatic coupling device suitable for use in a touch-sensitive organ keyboard (from *J. Acoust. Soc. Amer.*).

While there are many ways of realizing touch-sensitivity in an electronic organ, the electrostatic coupling device shown in Fig. 6 is notable for its low cost and simplicity. The attenuation vs displacement curve (the zero of the attenuation curve is arbitrary) is shown in Fig. 7. To obtain the rapid attenuation rate

[30] L. Hammond, U. S. Patent 2,230,826, applied for in 1939.
[31] D. W. Martin and A. F. Knoblaugh, "Loudspeaker accessory for the production of reverberant sound," *J. Acoust. Soc. Amer.*, vol. 26, pp. 676–678; September, 1954.

with a reasonably wide spacing of grounded surfaces, it is necessary to use a grounded channel as shown in Fig. 6, rather than a slit in a thin grounded shield. The depth of the channel must be sufficiently great that the required attenuation is obtained before the coupling strip leaves the channel. The device is described in a recent issue of the *Journal of the Acoustical Society of America.*[32]

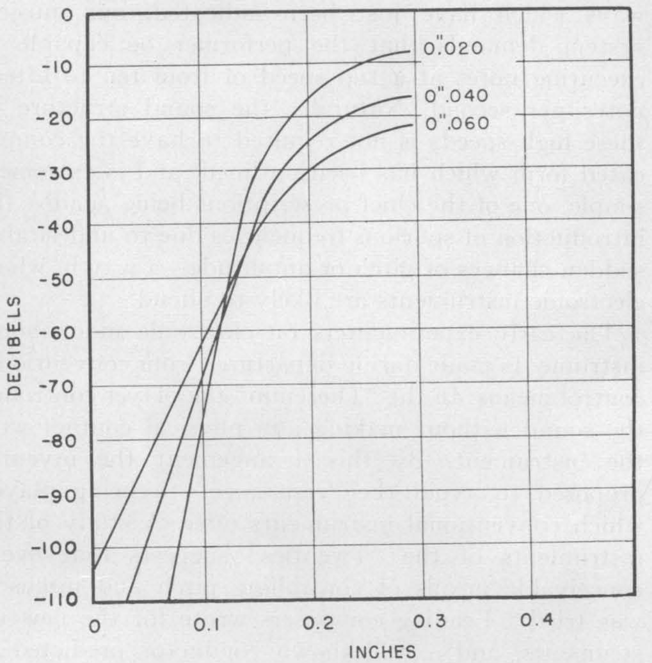

Fig. 7—Coupling in decibels versus position in inches of the coupling strip for various widths of grounded slot, obtained for the coupling device shown in Fig. 6 (from *J. Acoust. Soc. Amer.*).

From five to ten of these are normally used on each key for coupling harmonically related generators. When the highest harmonic and the dissonant harmonic coupling strips are adjusted to be a short distance farther out of the slot than the remaining coupling strips, a variation of timbre between the loud and soft sounds on the same manual may be produced. The difference between the various attacks which may be produced by the manner of operating the key is also accentuated, the slow attacks having an almost vocal quality due to the pronounced shift in timbre produced by the building up of the dissonant harmonics. An additional element of variety is introduced by the fact that the nature of these effects depends upon the timbre in use.

The writer's experience in playing a touch-sensitive organ has so far been limited to a single manual model which was built at the National Research Council of Canada in 1954. Oscillograms of two attacks produced on this model are shown in Fig. 8. A model now being constructed is designed to make the best possible use of piano-playing technique. The key linkage has been modified in favor of the production of fast attacks and comparatively slow decays. A holding pedal has been provided.

The Monophonic Instrument

Careful listening to a single musical part discloses that the performer on a standard monophonic instrument such as the saxophone, cello, or voice, has continuous and detailed control of the three musical parameters: pitch, loudness, and timbre.

While the ear can recognize several thousand distinct pitches, less than one hundred can be written on a musical score, and the development of significant musical ideas takes place in a considerably smaller range than this. Although our musical notation is not capable of providing the performer with more than a bare indication of the composer's desire to depart from the set of preferred pitches, players of expressive instruments do regularly make these departures and they constitute an important part of the effect produced by a monophonic instrument. The essential continuity of the pitch line in a monophonic instrument is an important point of departure from the polyphonic instrument of the organ type, and certain types of pitch flexibility are impossible on such a polyphonic instrument, the

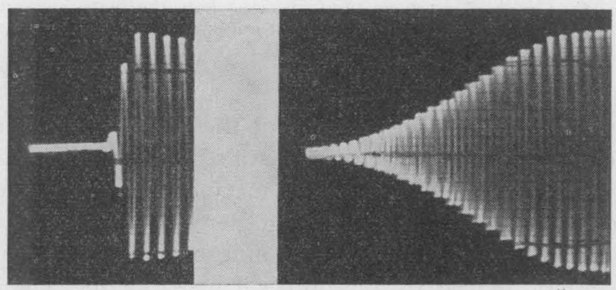

Fig. 8—Oscillograms of two attacks produced by the manner in which the performer operates the key of a touch-sensitive organ (from *J. Acoust. Soc. Amer.*).

basic feature of which is the separation of each musical part into discrete tones which are supplied from separate generators. The monophonic instrument is thus the most important musical instrument, and the starting point of all musical thinking; and the polyphonic or organ-like instrument is simply an expedient necessary in view of the difficulty of assembling the required number of monophonic instruments and performers.

Fig. 9 is a graph of pitch vs time showing how a performer on an expressive instrument might approach and perform a sustained note. The section shown at 1 is a slide or a portamento; the intensity of the note, which is not shown, rises from a low value so that the listener gradually becomes aware of the slide as the true or written pitch of the note is approached. Part of the effect of such a slide on the listener is one of smoothness. When the slide is prolonged, however, the effect produced is not related to that produced by a stationary note. The section shown at 2 is an off-pitch

[32] H. Le Caine, "Touch-sensitive organ based on an electrostatic coupling device," *J. Acout. Soc. Amer.*, vol. 27, pp. 781–786; July, 1955.

note which is purposely performed, perhaps about one-third of a semitone below the written or true pitch, and produces in the listener a feeling of unrest, possibly because the true pitch is anticipated. The section shown at 3 is performed on true pitch, but without vibrato. Finally, in the section shown at 4 a vibrato is added gradually, modifying the shrill effect of the section without vibrato. Thus the performance of the note comes to a close. While the listener is not usually aware of these effects as such, he would describe the above performance as having "warmth," or being "alive"; while a note begun and ended on the written pitch, situated among notes begun and ended in similar fashion, all having a constant vibrato, would be described as "mechanical."

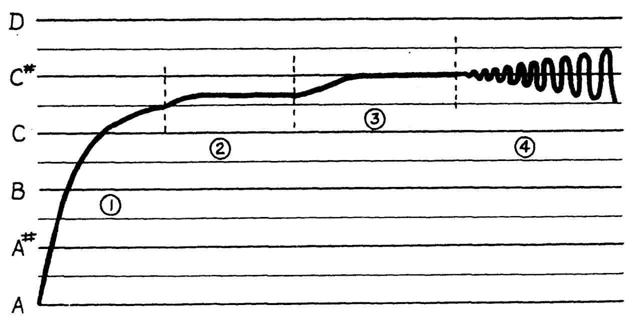

Fig. 9—Graph of pitch vs time, showing how the performer on an expressive monophonic instrument might approach and perform a sustained note.

The variation in intensity of the note which constitutes the attack and decay has already been discussed. The manner in which the intensity of the sound builds up in a musical instrument, together with the other processes which occur at the beginning of a note, are characteristic of the various musical instruments. The attack and decay of most of the expressive instruments can, however, be modified by the performer, although the nature of such control is far from ideal. In addition to these changes of intensity, there is a period during a sustained note when the intensity may be increased or decreased at the will of the performer, the time constant of such a process being considerably greater than one-tenth of a second.

A performer on some conventional instruments, such as the human voice, can vary the harmonic spectrum independently of frequency and intensity. Some instruments, such as the cello, have only a small range of variation: in others, such as the saxophone, the harmonic spectrum is closely related to the intensity. In all expressive instruments, including the concert harmonica, the variation of harmonic spectrum, even though it may in some cases be rather small, plays an important role in setting up the sound patterns with which we are familiar. This fact may be appreciated by noting the difference in effect produced between a line of notes played on the expressive instrument in question, and the same line of notes played on an electronic organ, even though the average harmonic spectrum may be imitated quite closely. In some cases, notably the human voice, the ability of the instrument to change its harmonic spectrum clearly enlarges its expressive power. In other cases, it may be only the lack of the accustomed diversity of effect in the electronic counterpart which causes the listener to raise the derisive cry, "electronic tone!"

In addition to being able to vary the sound in the ways which have just been indicated, our musical system demands that the performer be capable of executing notes at a top speed of from ten to fifteen notes per second. Naturally the sound structure at these high speeds is not required to have the complicated form which has been outlined, and is extremely simple, one of the chief prescriptions being against the introduction of spurious frequencies due to undesirably sudden changes of pitch or amplitude—a way in which electronic instruments are likely to offend.

The early experimenters on electronic monophonic instruments made daring departures from conventional control means. In the "Theremin" the player controlled the sound without making any physical contact with the instrument. By this arrangement the inventor proposed to avoid the "resistance" to being played which conventional instruments offer. A study of the instruments of the "Twenties" suggests that every conceivable means of controlling pitch and intensity was tried.[33] Leading composers wrote for the new instruments, and a well-known conductor predicted in 1929 that within a few years the conventional instruments, with their limitations and unnecessary playing difficulties, would have disappeared completely. Several monophonic instruments reached the production stage in Europe, and the "Theremin" was produced in the United States in the early "Thirties." The commercial success of these instruments was limited by the unsatisfactory state of electronic devices (tubes with ac-operated filaments were still a novelty). The inventors, in their eagerness to explore new musical effects, gave little thought to the prevention of clicks and other unpleasant sounds, or to making their instruments playable. When the intellectual exuberance of the "Twenties" gave place to the more conservative atmosphere of the "Thirties," development of the monophonic instrument was concentrated on the problem of producing an instrument which would stay in tune, sound pleasant, and be easy to play. The commercial instruments of the "Forties" succeeded admirably in these regards; nevertheless, the important orchestral combinations, both large and small, will still be found to consist almost exclusively of instruments invented more than seventy-five years ago, and we are forced to conclude that the problem of producing an electronic monophonic instrument to supplement or replace the conventional monophonic instruments is still unsolved.

[33] "Electronic Musical Instruments, A Bibliography," 2nd ed., Tottenham Public Libraries and Museum, London, Eng.; 1952.

The Electronic "Sackbut"[34]

In beginning work on a monophonic instrument in 1945, the writer started with the idea that the three coordinates of space should correspond to the three musical attributes: pitch, loudness, and timbre. The vertical direction was to correspond to loudness by analogy to the touch-sensitive keyboard instrument; the horizontal direction was to correspond to pitch by analogy to the arrangement of the musical scale on the keys of keyboard instruments, and the remaining direction was to correspond to one chosen subparameter of timbre. Instead of using as a control means a motion in the given direction, the control surface was made very stiff, and the performer concentrated his attention upon exerting appropriate components of force in the three directions. A number of control surfaces were provided; these control surfaces, in fact, constituting the keys of a standard keyboard. Thus it was intended that continuous variations of pitch, loudness, and timbre should be set up by a pattern of varying forces applied by the performer's finger on an individual key, while transformations in the pitch coordinate, in steps corresponding to the musical scale, would be made when the performer moved to a new key.

Much the most interesting of these control means is the association of continuously variable pitch with horizontal force applied to the key. The first record of its application is contained in a patent by Martenot.[35] Here a small horizontal displacement of the key varies the capacity in one of the radio-frequency oscillators of a heterodyne audio oscillator. When applied in this manner, the range of continuous variation of oscillator frequency must be kept small, otherwise playing becomes difficult at the low end of the keyboard. In order to use this control for producing a pitch variations of the type shown in Fig. 9, it is necessary first to arrange the pitch control so that the application of the same force or displacement on any key causes the same pitch change. The operation may then be greatly improved by making the relation between pitch and horizontal force as shown in Fig. 10. The sensitivity to horizontal force is seen to increase as one gets farther from the normal pitch associated with the key. In the normal playing range, that is, about half a semitone on either side of the standard pitch, the sensitivity should not be greater than 0.02 semitones per ounce, in order to permit rapid operation of the keys. The hoirzontal force need not then be controlled to better than one or two ounces except on long sustained notes, and an average vibrato requires an oscillating force of about eight ounces. About half a semitone on either side of standard pitch the sensitivity should increase to a value sufficiently great to reach the maximum pitch excursion at less than five pounds force. When the range is an octave on either side of standard pitch, the sensitivity must be increased about ten times, or to 0.2 semitone per ounce. With this relation between pitch and horizontal force, the performer feels that the sensitivity is approximately constant, as long as he confines himself to the type of pitch variation found in conventional music, since the wide deviations from standard pitch are done rapidly and usually at low intensity, and little accuracy is required. When applying large horizontal forces, it is helpful to depress keys below the key being sounded. A slip-proof surface on the key is also useful.

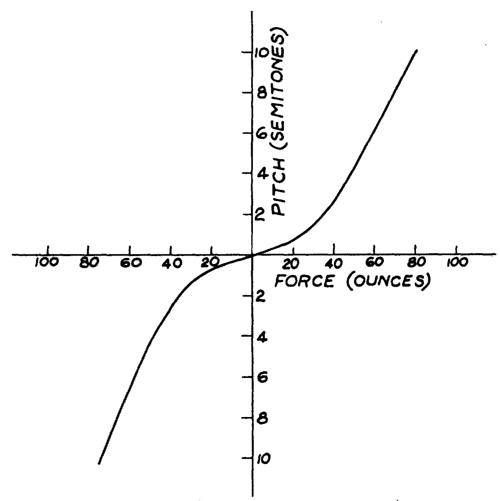

Fig. 10—Desired relation between pitch and horizontal force on the key in the electronic "sackbut."

To start a note off-pitch and gradually bring it toward the correct pitch, it is a simple matter to approach the keyboard at a slight angle to the vertical, and, during the production of the note, gradually remove the horizontal component of force. A portamento is done in much the same manner as that used by the player of a stringed instrument. The key being left is first forced in the direction of the new key; while the force is increasing, the key is dropped and the new key is depressed with no horizontal force applied. Thus the pitch moves in the direction of the new note, transition becoming ever more rapid, so that the listener is aware principally of the smoothness of the transition. For a satisfactory portamento the keyboard time constant must be very short; that is, the springs which return the keyboard to its normal position must be as stiff as possible. As constructed, the maximum horizontal displacement of the keyboard was about 0.001 of an inch, and the return-spring stiffness was 5,000 pounds per inch. It will be seen from the circuit diagram, Fig. 11, that a smoothing filter is also included. This helps to avoid irregular variations of pitch which are not intended by the performer, but which are due to improper execution of the movements described. Needless to say, the constants of the filter are such that no perceptible glide effect is caused by the filter itself. Vibrato

[34] The original sackbut is a thoroughly obsolete instrument. This choice of name was thought to afford the designer a certain measure of immunity from criticism.

[35] M. Martenot, U. S. Patent 1,853,630, applied for in 1930. (French patent application filed in 1928.)

is produced directly by the performer. The limitations inherent in mechanically-produced vibrato, which have been discussed in the section on electronic organ design, are thus avoided.

A simple circuit which gives uniform pitch sensitivity over the whole keyboard is shown in Fig. 11. Force exerted on any key is applied to a stiff beam which forms the grounded plate of the tuning condenser of a radio-frequency oscillator. The frequency change caused by the very small motion of the beam is converted to a dc voltage by a discriminator in which the separation of the tuned circuits has been made considerably greater than that used for fm detection. By controlling the separation of the tuned circuits and the relative coupling of each to the oscillator, a relation between force on the beam and pitch of the final oscillator, similar to that shown in Fig. 10, may be achieved.

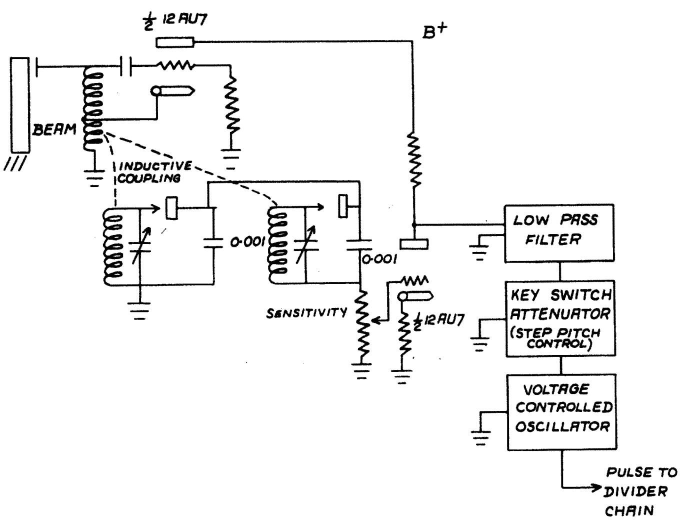

Fig. 11—Pitch control circuit which provides a relation between pitch and horizontal force on the key, of the type shown in Fig. 10.

The vertical force controls the loudness, thus enabling the player to determine the attack and decay of the note in addition to producing crescendo and diminuendo effects. Since there is only one control device for the whole keyboard, no engineering problem is involved. The musical considerations have been discussed earlier under "The Touch-Sensitive Organ."

Control of the timbre was removed from the key and put in charge of the left hand. The controls are arranged so as to stay where they are left; thus the left hand may be conscripted for use on the keyboard during rapid passages. Emphasis was placed on plastic control of the timbre, rather than imitation of special orchestral instruments or the provision of all conceivable timbres. Thus no stops were used, and the main controls are continuous, and divided up as nearly as possible so that a given change of position corresponds to a constant change of sensation. They are light, and the motion is restricted to not much over an inch. The controls may thus be moved fast enough to change the timbre during the attack of a note. A timbre vibrato[24] may be used. Timbre patterns of the same nature as those described earlier as characterizing existing instruments may be set up. The possible variation of timbre is of course much greater than that found in the familiar musical instruments. In addition to the timbre variations produced under the direct control of the player, an increase of brightness with intensity is provided by the use of nonlinear circuits. The only justification for this for this procedure is that it makes the tones sound more "natural."

The timbre controls are organized along the lines discussed in an earlier section. One control is a basic waveform control, which provides the basic waveforms which are found in musical instruments, such as square-wave, sawtooth, pulse, in addition to others. This is a two-dimensional control operated by moving a knob in a plane with the index finger. One dimension corresponds to brightness, and the other to octaveness. While this division is by no means an entirely logical one, it has been found of considerable help to the performer in arranging the timbres in his mind and realizing them on the instrument.

Control of the basic waveform has been obtained by the motion of a conducting felt pad over the surface of a disc of resistor card material. A recently revised form, shown in Fig. 12, consists of a circular plate divided into a number of separate conducting sections which are connected to various waveforms derived from the divider chain, which itself supplies square-waves at octavely related frequencies (f, $2f$, $4f$, $8f$ on the diagram). A conducting disc, which is shown by the dotted circle, is moved over the conducting sections, and is capacitively coupled to them. While the points corresponding to the basic waveforms of the various classes of instrument have been marked on the diagram, it has been pointed out earlier that timbre plays only a limited part in instrument recognition. Thus, if the basic waveform and formant controls are set to produce an

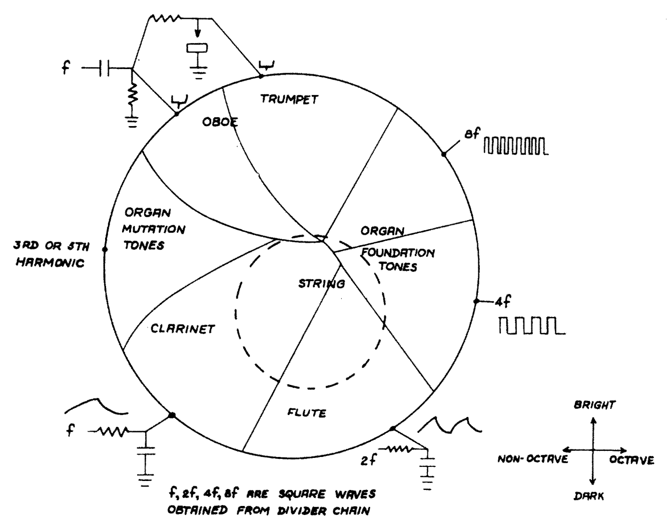

Fig. 12—Basic waveform control in the electronic "sackbut." A circular plate is divided into a number of conducting sections insulated from each other, shown by the solid lines. A conducting disc is capacitively coupled to the conducting sections. The dotted circle shows the relative size of the disc and the position where the basic waveform is approximately a sawtooth.

harmonic spectrum appropriate for a cello-like effect, the sound does not remotely suggest a cello if a fast attack is used.

The other timbre control, shown in Fig. 13, is the position of two formants which may be controlled together or singly by the thumb. Continuous control by the inductors covers a range of two octaves which may be located anywhere in the musical spectrum by auxiliary controls. Other auxiliary controls also control the Q of the formant circuits.

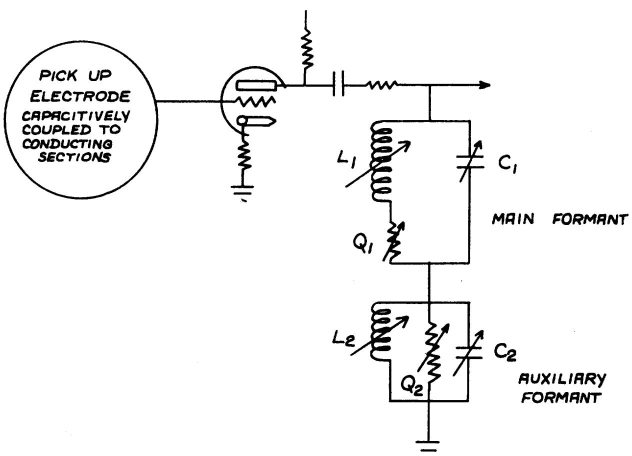

Fig. 13—Formant control in the electronic "sackbut."

The left hand normally occupies the position shown in Fig. 14 where the thumb controls the formant circuits, the index finger controls the basic waveform, and the three remaining fingers are available to operate keys which control departures of the waveform from simple periodicity, such as by frequency modulation of the pitch generator with a 20-c square-wave, or with narrow-band low frequency, or with wide-band noise.

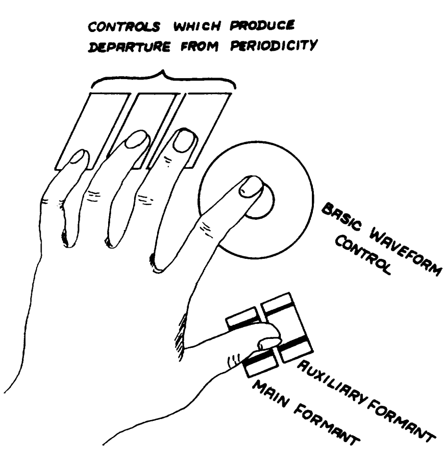

Fig. 14—Arrangement of timbre controls in the electronic "sackbut."

These controls are continuous, increasing force resulting in increasing depth of modulation, and are of the spring-return type, since they are seldom used for long periods.

In order to facilitate moving the range of the instrument up and down by octaves, all the waveforms for the timbre control circuits are derived from a chain of scale-of-two counters which are driven by the voltage-controlled oscillator. Changing the range of the instrument by octaves then involves simply moving all the take-off points together up or down the chain the required number of units. Since accelerated playback performances are now so frequently required by composers and arrangers, it is well worth adding several octaves to the lowest range normally required for direct performance so that the performer can record at a speed of one-quarter of the playback speed and have low notes on the record. A "monitor" output one or two octaves higher in pitch than the recorded output is also useful. The lowest note which can be used in direct performance is lower than one might expect. While no standard reproducers are capable of making a pure tone of 15 c loud enough to be musically useful, a musical tone having a pitch corresponding to 15 c may be quite effective when heard through a standard reproducer.

Development of this instrument stopped in 1948; however, further development has been undertaken recently at the National Research Council of Canada. The pitch flexibility of the instrument is being extended by combining a continuous pitch control with the keyboard. The combination is made in such a way that motion of the finger backward along any key transfers control from the key control to the continuous control without introducing any discontinuity in the sound. Thus it is possible to terminate a figure started on the continuous control, on a key on the keyboard, and vice versa. It is hoped that the integration of the two control means will be sufficiently good that the pitch flexibility obtained by the use of a continuous control may be combined with the ease of playing rapid passages which is characteristic of the keyboard.

A helical-spring reverberation device used in the earlier instrument will be replaced with one based on magnetic recording techniques. Using a magnetic tape feedback loop, it is possible to add to a musical instrument a reverberation pedal, shown in Fig. 15, which functions very much like the sustaining pedal on a piano, in that when the pedal is down, notes are prolonged after release of the key, and when the pedal is released the stored energy disappears rapidly. The decay constant of the sound may, however, be controlled accurately by the displacement of the pedal—a type of operation which is very difficult to achieve consistently with a damper pedal. Control of the reverberation by the signal itself offers new possibilities in suppressing undesired transient effects without introducing undesirably long decay times.

The Monophonic Instrument as an Organ Auxiliary

The Hammond Organ has a pedal auxiliary unit which consists of a monophonic oscillator.[36] Monophonic oscillators are sometimes found on the manuals of a small organ, primarily as a means of increasing the

[36] R. L. Eby, "Electronic Organs," Van Kampen Press, Inc., Wheaton, Ill., pp. 97–140, 1953.

resources at comparatively small expense.[37,38] Since the monophonic oscillator is not synchronized with the main organ generators, such devices also produce musically useful beats. Within limits, they also permit solo and accompaniment to be played with one hand. Similar devices have been provided on the pipe organ to achieve this last result,[39] but were rather infrequently used by organists.

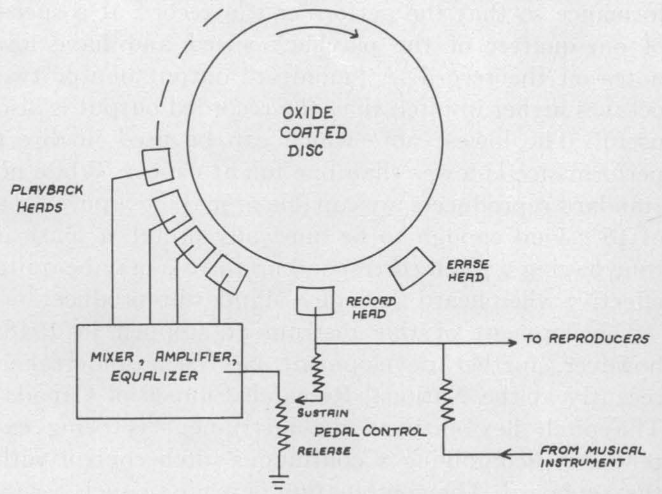

Fig. 15—A "reverberation pedal" which may be fitted to an electronic musical instrument and which performs in a manner similar to the sustaining pedal of the piano.

European Electronic Monophonic Instruments

An electronic monophonic instrument manufactured in Germany, the Hohner "Electronium,"[37] is superficially similar to the Hammond "Solovox," and is mounted in an accordion case. Control of the loudness is obtained through operation of the bellows.

The "Ondes Martenot"[40] appeared in its earliest form in France in the late "Twenties." Some of France's leading composers have written for it. The most celebrated instance was its use in "Joan of Arc at the Stake" (Honneger, 1938). It was heard in Boston in 1950 in "A Concerto for Ondes Martenot and Orchestra" by Andre Joilvet.[41]

A new monophonic instrument, the "Melochord,"[42] shown in Fig. 16, which has become an indispensable tool in the creation of electronic music in the Studio for Electronic Music at Cologne, is an electronic keyed instrument with two independent monophonic playing ranges, and can function as a normal musical instrument, as well as produce the effects required for electronic sound composition. Normally each playing range of the "Melochord" contains a separate tonal generator and sound filters of various kinds belonging to each generator. Each playing range also has a control device which functions to produce known attacks and decays, such as the sound produced by wind and plucked-string instruments. There is also a vibrato generator. Each playing range is provided with a swell pedal for controlling the loudness. Naturally, the studio is provided with echo chambers, tape loops, and many other devices both well-known and new, and the policy followed in developing the instrument is to include on it only those devices directly connected with the sound generation.

Fig. 16—"Melochord" of Studio for Electronic Music at Cologne. (Photograph courtesy of Nordwestdeutscher Rundfunk.)

A particularly interesting feature of the "Melochord" is the sound filter which can be tuned by the operation of the keys in step with the pitch of the generators. The "traveling formant" is obtained by means of a special set of normally closed contacts on the keyboard. By means of these contacts all of the condensers which happen to be on the left-hand side of the key touched, are separated from the series of condensers connected in parallel. The sum of condensers thus remaining on the right-hand side serves for tuning the parallel resonant circuit formed by these condensers and an inductance, which latter is also variable.

In addition to adding the outputs from the two keyboards, as is usually done, they may be connected to a ring-modulator and mixed in multiplication. A few examples of the effects which may be obtained with this instrument are given in the reference quoted above.[42] By turning off the second generator, and including the step-by-step filter in Channel 1, it is possible to determine the pitch and the nonsteady processes by playing the keys of Channel 1; while playing the keys of Channel 2 influences the timbre. By turning off Channel 2 and connecting a noise generator, it is possible to produce a noise sound having pitch, which is reminiscent of sound produced by the wind. By connecting impulse

[37] See *Instrumentenbau Zeitschrift*, (special electronic instruments number), particularly, "A technical survey of electronic instruments," pp. 170–172; April, 1954.
[38] Eby, *op. cit.*, pp. 123–129.
[39] J. I. Wedgewood, "A Dictionary of Organ Stops," Vincent Music Co., London, Eng., p. 100, 1905.
[40] Dorf, *op. cit.*, pp. 180–181.
[41] E. Vuillermot, "Odd concerto for Ondes Martenot and orchestra," *Christian Science Monitor, Magazine Section;* March 11, 1950.
[42] H. Bode, "The Melochord of the Cologne Studio for Electronic Music," (see footnote 58).

noises to the input, various "plucked" effects having various timbres may be obtained. Again, the music of an orchestra may be connected at the generator input; then the music appears "modulated" with vocal colors.

Another instrument developed for the Cologne Studio is the "Electronic Monochord,"[43] shown in Fig. 17. This instrument was developed from the "Trautonium" which appeared in the late "Twenties." The new version may be used either in the direct performance of music, or for the composition of electronic music. The new instrument contains two monophonic electronic sound producers in one cabinet. While in some versions several oscillators having harmonically related frequencies have been included, this was not considered necessary for an instrument designed for electronic sound composition. In describing the instrument, Trautwein emphasizes the necessity for the player to have a freely variable frequency range at his disposal. Some earlier models used thyratrons as the frequency determining element, and potentiometers with a linear taper as the control element. By proper choice of the voltage across

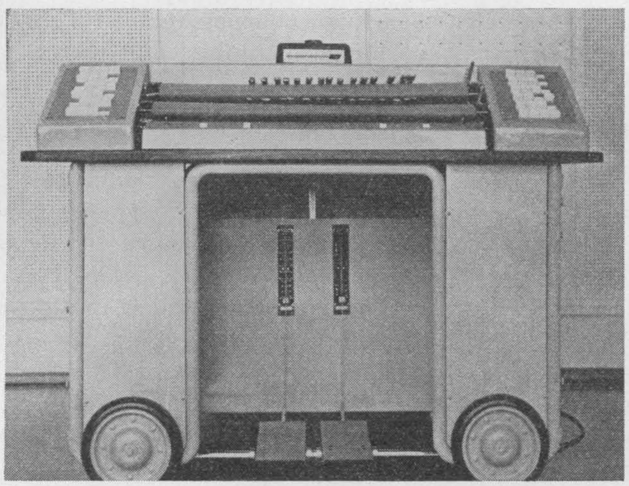

Fig. 17—The "Electronic Monochord" of the Studio for Electronic Music at Cologne. (Photograph courtesy of Nordwestdeutscher Rundfunk.)

the potentiometer and the fixed grid bias, it was possible to get three octaves which were approximately logarithmic. In the "Electronic Monochord" at the Cologne Studio, the grid resistor is the control element. It is coiled around a drum of elliptic cross-section; the return connection is provided by a piece of braided material placed a few millimeters distance from the drum. The spacing of the winding in this design can be so arranged that a semitone step is the same length anywhere on the keyboard. Elastic keys have been placed above the playing device so that desired frequencies may be selected easily. There are five keys over each octave which give a pattern similar to that of the black keys of the standard keyboard. The keys are, however, tuned to the pitches required in the composition.

[43] F. Trautwein, "The Electronic Monochord," (see footnote 58).

The basic waveform of the device is a sawtooth with an exponential curve of amplitude. The low notes are strongly exponential in character, and thus are richer in overtones than the high notes, with their almost linear curves. Pulses may also be taken from a cathode resistor. Formant filters serve for the formation of tone colors. These filters consist of band filters, acceptor circuits, and suppression filters, which permit selection of a widely variable frequency response.

For the concert hall a loudspeaker output of 150 w, producing a level of 110 db is considered necessary. On each manual two devices have been provided for controlling the signal energy: a pedal, and a control consisting of a pressure-dependent resistance which is placed underneath the elastically supported playing device.

The Coded-Performance Instrument

The distinguishing feature of coded or mechanically performed music is that it is completely written down in advance, and the performance consists simply of carrying out the written instructions. The difference between this kind of music and conventional music may not seem very great, but the complete writing down of a musical performance has been attempted only in certain special cases. In the early days of the player piano, the rolls were punched directly from the written music, but these were soon replaced by "hand-played" rolls. In view of the mechanical sound of the "hand-played" rolls when played on the average player piano, it may seem surprising that a workable solution to the problem of writing down the nuances of tempo was never obtained. Seashore's work with the piano-camera has revealed, however, that time differences of one-hundredth of a second may be significant in piano performances.[44] His work also shows that the distortion of the tempo in rubato passages may amount to one hundred per cent of the bar length, and that such distortions are organized in complicated patterns. These patterns have never been analyzed directly, but are learned by the musician by a subconscious process, as canons of musical or artistic taste. When preparing for a performance, a performer may choose between a number of well-known alternatives, or he may invent new patterns, both processes producing a variation in the performance of different artists which is known as "interpretation." Nevertheless, there is a great deal of information in the final performance which is known to both performer and composer, yet does not appear on the written music. The same may be said of the pitch, loudness, and timbre patterns which appear in the final performance. The codification of these patterns constitutes a formidable task to be completed before the direct production of familiar music can become routine. The production of novel effects, and the per-

[44] C. E. Seashore, "Objective Analysis of Musical Performance," Studies in the Psychology of Music Series, vol. 4, The University of Iowa, Iowa City, Iowa; 1936.

formance of *avant-garde* compositions are likely to be much more successful, since for the presentation of these works the task of translating the very large body of musical conventions into terms appropriate to the apparatus need not be completed so thoroughly.

In spite of the lack of knowledge concerning the precise nature of the unwritten parts of music, composers have always shown an interest in writing for mechanical instruments. Handel wrote a considerable amount of music for the barrel organ, giving instructions for the placing of the pins. Stravinsky and others have written music to be punched directly onto player piano rolls. Modern mechanical or "synthetic" music began perhaps about 1000 A.D. with the invention of clockwork, although mechanically-operated sound-producing devices were used earlier than this in connection with religious services. The continuous invention of mechanical instruments from the advent of clockwork to the present day forms a fascinating story.[45] One of King Henry VIII's prized possessions was a player-virginals. Maelzel constructed a mechanical orchestra of over forty instruments, in which, in addition to the sound-producing mechanism, there were clockwork figures which actually went through the motions of playing their instruments.

Electronic Coded-Performance Instruments

The first electronic "synthetic music" instruments were naturally perforated-roll-operated, following the example of perforated-roll-operated pianos and organs. There is, of course, no reason why a performance on a pipe organ with a properly-programmed perforated roll should be inferior in any way to a performance by a human being, since all the human performer can do is to close the same switches.[46] It is worthy of note, however, that the vast number of organ records now in print are hand-played, in spite of the obvious superiority of the roll-operated organ as a performer.

The first public demonstration of "synthetic music" made by electronic devices was at the Paris Exposition of 1929, where a roll-operated device consisting of four monophonic electronic oscillators was shown with great success. Following the basic patent covering this device,[47] there are other similar French patents. In one of these,[48] a number of different devices are described, that allow the composer or arranger to draw by hand the sound envelope. In one form of the invention, the arranger engraves a groove in a suitable support which varies either in depth or in position at right angles to the time axis. When the music is reproduced, a needle following the groove operates an optical wedge to control the light passing through a sound-on-film recording to a photocell. In another form of the invention, the arranger draws by hand in conductive ink, a mark of varying width or position which is read by a series of brushes to set up the sound envelope. As a sound source, the inventor uses a "sound library" (sonothèque) consisting of suitable supports on which are recorded by any known method the various notes of the various instruments, in addition to vocal sounds and other noises. As an alternative, synthesis from pure tones is mentioned.

The first United States patent on an electronic synthetic music device was applied for by Hanert in 1945,[49] and assigned to the makers of the Hammond Organ. Hanert described monophonic oscillators operated by a punched-card system which overcomes some of the limitations of the perforated roll. He paid special attention to the problem of making it as easy as possible to alter the performance until a satisfactory result was obtained. The operation of Hanert's electronic music synthesizer was based upon the breakdown of a tone into characteristics such as frequency, intensity, growth, duration, decay, portamento, timbre, and vibrato.

Animated Sound

While the use of electronic generators to replace the prior art generators such as violin strings, pipes, chimes, and so forth, evidently increases enormously the scope of a mechanical instrument, the first really new development in the art of mechanical music since 1000 A.D. was the idea of abandoning the time-honored parameters: pitch, amplitude, and timbre, for one single parameter, that associated with the sound wave. Thus any sound whatever, including the sound made by a 100-piece symphony orchestra[50] may be considered simply as a particular function of time. Once this function is specified, the sound may be heard by the use of suitable apparatus. While this revolutionary new point of view was implicit in the theory of the propagation of sound waves, and later pointed up by the invention of the phonograph, really convenient apparatus did not appear until the sound film.

McLaren of the National Film Board of Canada, has, since 1939, made a special study of this method of producing sound.[51] His beautiful and imaginative films with hand-drawn sound were responsible for a renewed interest in all methods for the production of sound without direct performance upon a musical instrument. McLaren made no attempt to imitate the conventional instruments, but used sound waves having simple and easily drawn shapes. A diagram of radiating lines placed

[45] "Oxford Companion to Music," Second American Edition, Oxford University Press, New York, N. Y., pp. 549–556; 1943.

[46] The automatic player manufactured by the Moller Organ Co. is capable of playing six independent tonal lines at the same time. (See W. H. Barnes, "The Contemporary Organ," J. Fisher Bros. New York, N. Y., p. 315, 1948.) Thus this mechanical performer has six "hands."

[47] E. E. Coupleux and J. A. Givelet (France), U. S. Patent 1,957,392, applied for in 1930.

[48] L. Lavallee, French Patent 806,076, applied for in 1936.

[49] J. M. Hanert, U. S. Patent, 2,541,051, applied for in 1945.

[50] Because of the enormous amount of information involved, the hand drawing of such a sound is of course not practicable.

[51] R. E. Lewis and N. McLaren, "Synthetic sound on film," *J. Soc. Mot. Pict. Engrs.*, vol. 50, pp. 233–247; March, 1948.

under the film was used to obtain the basic spacing required to give the desired pitch. Fig. 18 shows a somewhat different method used by McLaren for putting a sound track together. A series of variable density patterns, seen in a card file at the right of the figure, were photographed through an adjustable mask seen at the left. In McLaren's most recent film, simple marks made with a needle point directly on 35-millimeter black emulsion film were used. While the marks are easy to draw, the sounds so produced are very complex from the point of view of pitch, loudness, and timbre, and are well suited to the development of the complex rhythms which have interested composers since the turn of the Century.

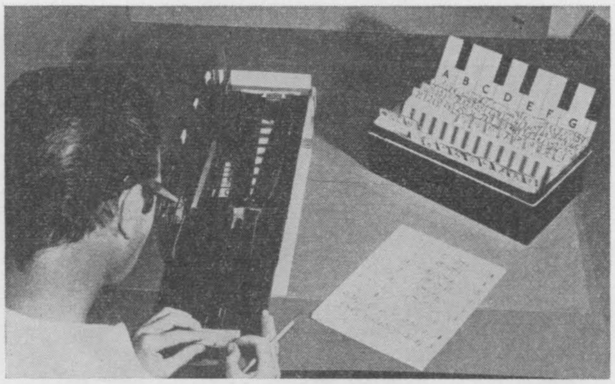

Fig. 18—One of the animated sound techniques developed by Norman McLaren of The Natl. Film Board of Canada. A series of variable density patterns seen in the card file at the right of the figure are photographed through an adjustable mask seen at the left. (Photograph courtesy of The Natl. Film Board of Canada.)

Recent Electronic Coded-Performance Devices

An electronic method of direct sound production based on McLaren's work is due to Kendall, also of the National Film Board of Canada. In Kendall's method[52] the adjustable mask shown in Fig. 18 is replaced by a hand-drawn sound envelope which is applied to the output of an electronic generator by means of a cathode-ray tube curve reader. This instrument is being developed by the Canadian Marconi Company.

A great deal of interest was aroused earlier this year by the Radio Corporation of America's disclosure of a perforated-roll-operated device, designed by Olson at the RCA Laboratories, Princeton, N. J. Olson's apparatus uses a pair of monophonic oscillators controlled by a coded record on a perforated roll. The holes control the pitch, timbre, growth, duration, intensity, and decay of the note sounded by the monophonic oscillators. The circuits and mechanical devices used to achieve this control are described in detail in a recent paper.[53] The oscillators are used on alternate notes so that the decay portion of one note may be continued during the attack portion of the next note, the combination thus producing what might be regarded loosely as a single monophonic part or line of notes. A sufficient number of individual parts to form the musical composition are combined by multiple recording.

The versatility of the device is shown by the fact that intelligible speech can be produced from a very simple code (525 bits per second). It may be noted in passing, however, that to synthesize with this apparatus the familiar sound produced by a glissando on the keys of a piano with the sustaining pedal down, would require forty-four individual record tracks. This difficulty arises when an effect similar to glissandos, arpeggios, and rapid figures on polyphonic instruments is required, and represents a sacrifice of convenience which must be made to gain the independence of parts and pitch flexibility which can be obtained with a monophonic instrument.

New Musical Horizons Through Electronics

Up to this point we have considered the problem of fitting electronic musical instruments into the existing musical scheme. It is here, of course, that the significant commercial developments of electronic musical instruments are to be expected. The nature of our musical system, however, is dependent to a large extent upon the musical instruments for which composers have been writing. If electronic instruments have disappointed us by not immediately replacing archaic instruments constructed of such nonmodern components as catgut and horsehair, this is due in part to the fact that electronic techniques of sound production belong to a musical system which has not yet been evolved. The experiments directed toward the discovery of this musical system made by workers in the "Twenties" were enthusiastic and promising, but were slowed down by the economic hardships of the "Thirties" and World War II. In the rebirth of interest in electronic music which took place after the war, sound storage devices have played a large part.

Before a musical performance can be presented it must be conceived or planned by the composer or the arranger. To aid in building a mental impression of what the final performance will be like, composers have traditionally used three methods: (a) the parts are played over separately on an instrument, a mental impression of the total effect being thus built up; (b) one or more parts are played over slowly and speeded up in the imagination, and (c) short sections are played over on an instrument and joined together in the imagination. Modern sound-storage devices allow a musical composition to be put together by three well-known recording techniques which carry out physically the three processes traditionally used by the composer in the first stage of conceiving the composition. They are: multiple recording, accelerated playback, and splicing of the record. The sound-composition techniques up around these recording processes combine

[52] A. Phillips, "Osmond Kendall's marvelous music machine," *Maclean's Magazine*, pp. 22–23, 52–56; June 11, 1955.
[53] H. F. Olson and H. Belar, "Electronic music synthesizer," *J. Acoust. Soc. Amer.*, vol. 27, pp. 595–612; May, 1955.

direct performance of parts of the composition with mechanical assembling of other parts. In the United States, experiments on sound-composition processes are being conducted by the "Music for Tape Recorder" group (V. A. Ussachevsky, Otto Luening, John Cage, Christian Wolff, Earl Brown, and Louis and Bebe Barron). The work of this group, including Cage's "Music for Prepared Piano" combines natural and electronic sounds with sounds which have been altered by the recording process. In Europe, the Musique Concrète group (Pierre Schaeffer, Pierre Henry, and their associates) limit themselves to natural or "concrete" sounds picked up by a microphone.[54]

The Musique Concrète group has found that the arbitrary cutting of a piece of recorded material which can be reproduced as often as desired leads to considering this piece as a "sound object," either an elementary one, or one capable of being broken down further. Because it is stored in a permanent form, it can be analyzed physically and musically and a judgment may be made of its value when taken by itself, dissociated from the group of phenomena from which it has been taken. It can be used as it is, or it may be transformed by various electroacoustic processes to give birth to new sound objects.

The assembling and evaluation of sound objects is part of the work of the Musique Concrète group. Their extensive library includes such sound objects as the falling of a drop of water, the sound of a gong without the impact by which the sound is produced, and the click of a Chinese block. This sound library recalls the "sonothèque" of Lavallee, and Respighi's use of the recorded voice of nightingales stored in an earlier form—the phonograph disc—and used as a complex sound object in "The Pines of Rome" (1924). The transformation of sound objects may be compared to Milhaud's creative use of a change of playback speed in the late "Twenties" to produce a chorus of voices singing above the pitch range of a normal voice. Schaffer has given in his book,[55] a fascinating account of the development of the ideas of "musique concrète" and of the processes which occur during the conception and putting together of a piece of "musique concrète."

Two pieces of apparatus used by the Musique Concrète group are the "Phonogène" which transposes the spectrum from one pitch to another by variation of tape drive speed, and the "Morphophone" which controls the sound envelope. Multiple recording technique and splicing of the tape record are used to assemble the sound elements so formed. The Phonogène, which is shown in Fig. 19 is a 24-speed tape recorder which uses a closed tape-loop. Twelve drive spindles may be seen, each having its own pressure wheel. The speeds correspond to the twelve semitones in the equitempered chromatic scale. The drive spindles may be engaged by depressing one key of a 12-key piano keyboard which does not appear in the figure. The motor speed may be changed by a factor of two to extend the number of tape-drive speeds to twenty-four. Rerecording to a constant speed tape recorder and back to the Phonogène allows further extension of the speed range. The Phonogène carries out a rigorous translation of the spectrum, while transposition on the well known musical instruments is not exact at all, since the harmonic spectrum varies within wide limits over the range of the instrument. The attack and decay are also varied with the transposition on the Phonogène, transposition to a lower pitch bringing about an increase in the time of build-up and decay, and an increase in the reverberation which accompanies the note. Conversely,

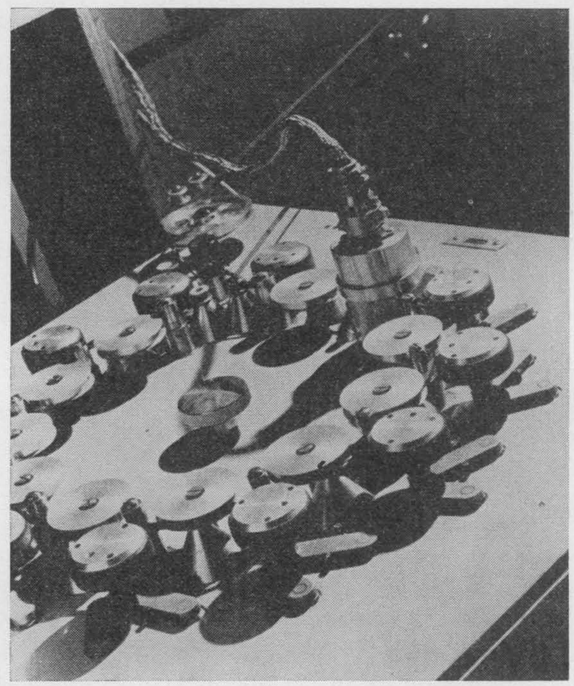

Fig. 19—The "Phonogène" of the Musique Concrète Group of the French Radio and Television System in Paris. A tape loop may be driven at twenty-four speeds using a keyboard control which is not shown. (Photograph courtesy of UNESCO.)

a note transposed to higher pitch will have a faster build-up and decay, and less reverberation. The term "complex note" is used to designate a superposition of simple notes such as a chord, or a sound obtained from sampling a sound complex. These sounds, as well as noises, vocal sounds, or rhythmic patterns formed by groups of notes, may also be transposed by the Phonogène. In the slide-Phonogène the tape may be run at continuously variable speeds.

The Morphophone is a closed-loop tape playback device possessing ten playback heads, each head connected to a preamplifier, the gain and response curve of which can be modified with the aid of simple filters. The outputs of the preamplifiers are mixed to feed the output amplifier. A primary use of the apparatus is to provide artificial reverberation of variable form and

[54] J. Poullin, "L'apport des techniques d'enregistrement dans la fabrication de matières et de formes musicales nouvelles. Applications à la Musique Concrète," *Onde Elect.*, vol. 34, pp. 282–291; March, 1954.

[55] P. Schaffer, "A la Recherche d'Une Musique Concrète," Editions du Seuil, Paris, France, 1952.

color, since the decay time of every sound phenomenon depends upon the preamplifier playback controls. Another device permits the superposition of an envelope belonging to one sound upon another sound; thus a plucked string attack may be imposed upon a normally steady sound.

Musicians have shown considerable interest in a mechanism for moving the source of sound about in space. It is a piece of apparatus which resembles that used for stereophonic projection, except that the distribution of sound output is determined by the composer or the conductor. Four loud-speakers are used: two placed in front of the audience, one above, and one behind. These are connected to four channels on synchronized tapes. When used in this way the space projection is known as "relief statique," "statique" meaning that the distribution of sound among the speakers is prearranged. Alternatively, a conductor or "executant," by moving a small magnetic unit through the air during a performance, can control the distribution of loudspeaker outputs by the relation between the movable magnetic unit and four stationary loops connected to the four loudspeakers. In a ten-day series of lectures and concerts given in 1953, organized by the Groupe de Recherches de Musique Concrète de la Radio-Television Française, American and French workers in the field of sound composition on magnetic tape "projected" their own recorded compositions. Alternatively, a five-track tape recording may be used, the conductor controlling during the performance the distribution of the sound on the fifth track, while the distribution of the sound on the other four is prearranged.

The music produced by the Musique Concrète group recalls Debussy's interest in Javanese music and the rhythmic experiments of Varèse in the "Twenties." Speaking in 1932, Stokowski,[56] who also found himself attracted by Javanese rhythms, predicted that one of the contributions made to music by scientific techniques would be the exploration of new and complicated rhythmic patterns which are too difficult for present-day performers and instruments. He mentioned in the same lecture the possibility of recording a particularly favorable note in the range of a singer and reproducing it at all pitches by sound-on-film recording technique. Here he probably had in mind Radio Station WCAU's photoelectric organ on the design of which he collaborated.[57]

One example of the work of the Musique Concrète group presents bursts of sound from a number of unrelated sources in a complicated rhythmic pattern. One of the sources is a single chord sustained on an organ. In another example, after striking a key on the piano, by variation of drive-speed, the pitch of the note is raised several octaves and returned to normal pitch, the time for this maneuver being about one second. This bizarre sound is combined with other previously recorded piano sounds which have also been "denatured" in a variety of ways. Again, the rhythmic patterns are complex. Poullin,[54] speaking of the numerous works of the Musique Concrète group, says, "Their first hearing may excite a lively interest, astonishment, indifference, or severe censure." (The writer believes that the second last reaction is rather rare.)

The approach of the Cologne Studio for Electronic Music is to dispense entirely, not only with natural or concrete sounds picked up by a microphone, but with preformed sounds of any kind. An entire issue of the technical magazine published by Nordwestdeutschen Rundfunks has been devoted to their work. The acoustical and musical bases for their viewpoint of music are explained, and the apparatus and musical work of the North-West German Broadcasting Station at Cologne are described. Only a very brief outline of this important development will be given here, and the reader is urged to consult the original publication.[58] This group has been concerned principally with discovering the essential nature of music which is "electronic" in the restricted sense of the word. Eimert[59] believes that the point of departure for electronic music is the rationalization of musical elements because of which music is no longer reducible to manual performance. Busoni regarded the world of sound as a continuum, of which the world of our traditional music was a very small part. Eimert sees in electronic music a means of permitting the composer to work in the whole continuum. The limits of playability are abolished, or replaced with the limits of audibility.

Eimert places electronic-acoustic phenomena in five classes:[60]

1) A simple tone, or a pure sinusoidal tone without overtones. These are not found in traditional music but are the basis of all musical sound processes. Sinusoidal tones cannot be used to build up a system of tones in the traditional sense since they have no "tonal" character.

[56] L. Stokowski, "New horizons in music," *J. Acout. Soc. Amer.*, vol. 4, pp. 11–19; 1932–33.

[57] "WCAU's photocell organ," *Electronics*, vol. 7, p. 157; May, 1934.

[58] "Technische Hausmitteilungen des Nordwestdeutscher Rundfunk," vol. 6, 1954. The papers from this volume which are listed below, have been translated by the National Research Council of Canada. Copies of the translations are available at a nominal fee from the Library, National Research Council, Ottawa 2, Can.
H. Eimert, "Electronic music"
W. Meyer-Eppler, "Terminology of electronic music"
F. Enkel, "The technical facilities of the electronic music studio of the Cologne Broadcasting Station"
F. Enkel and H. Schütz, "Magnetic-tape technique"
F. Trautwein, "The Electronic Monochord"
H. Bode, "The Melochord of the Cologne Studio for Electronic Music"
W. Meyer-Eppler, "The mathematical-acoustical fundamentals of electrical sound composition"
F. Enkel and H. Schütz, "The production of sound effects for radio dramas"
H. Eimert, "The musical situation"
K. Stockhausen, "Composition 1953, no. 2"
H. Eimert, F. Enkel, and K. Stockhausen, "Problems of electronic music notation."

[59] H. Eimert, "Electronic music," (see footnote 58).

[60] H. Eimert, "The musical situation," (see footnote 58).

2) A complex tone with harmonic partials, which is composed of a series of simple tones whose frequencies form an harmonic series. The "tone" of an instrument is a complex sound determined by the components of the series. In normal instruments the timbre can be varied over a comparatively small range. Electronics, now, for the first time, makes these components variable.
3) A tone mixture, in which the frequencies of the partials are not harmonically related to the fundamentals and cannot be expressed in terms of integral ratios. Mixtures of sinusoidal tones are not to be confused with chords: they have a higher binding level and can turn into "musical sound" much more readily than instrumental chords. In electronic music steady tone mixtures can be realized without effort.
4) A noise, which is determined by its specific character and pitch. The pitch of colored noise has approximate value only; the so-called "white noise," which extends over the entire auditory range, has no pitch at all.
5) A combination of two or more different complex tones sounded simultaneously; that is, an interval or a chord. In instrumental music "complex tone" and "chord" are clearly distinguished from one another. In electronic music, however, the tone mixture, with its new binding levels becomes a bridge between the two. Complex tones and mixtures can be composed electronically according to a prescribed composition arrangement.

The Electronic Music Studio of the Cologne Broadcasting Station contains three classes of equipment:[61] 1) electronic sound and noise producing sources, to provide the raw material for further processing; 2) electroacoustic shaping means, for the purpose of influencing the frequency spectra and the transient processes of sound phenomena—the methods used here are taken from communications techniques and yield sound phenomena which cannot be obtained by mechanical methods; 3) mechanical sound-recording apparatus for further processing of material obtained with 1) and 2).

1) One of the characteristics of the electronic sound-producers is that timbre is freely variable and is thus accessible as a new shaping element. The various available apparatuses for the purpose of generating the original sounds are: an Electronic Monochord, a Melochord (both of which have been described earlier in this paper), a generator of "white noise," and a number of standard laboratory audio-frequency generators. The possibility afforded by the Monochord of producing any desired musical scale conveniently and independly at fixed tone intervals is regarded as particularly valuable. A special noise source is used for the production of white noise. A beat-frequency oscillator is very useful for covering the entire audio-frequency range. For obtaining musical intervals accurately, audio-frequency generators with a comparatively large constancy are required. Commercially sold bridge-stabilized arrangements with decade frequency adjustments have a frequency accuracy of one part in a thousand, and have proven very satisfactory for this purpose.
2) A ring modulator is used to produce a multiplicative mixture of sounds which are quite different from the original sounds. An example of a multiplicative mixture is given later. Sounds are altered by playing back at speeds other than the recording speed. While the intervals remain unchanged, the transient processes are subjected to a far-reaching transformation. By playback at speeds greater than the recording speed, especially fine effects can be produced, which, owing to the size and weight of the acoustic apparatus which would be needed, could not possibly be attained by purely mechanical means. It is also possible to create echo times of extreme length by playing the record more slowly than it is recorded. Vibrato effects may be added by rhythmic tape-speed variation. For the production of restricted frequency bands from broad spectra, low-pass, high-pass, and band-pass filters are used. Eight octave filters having consecutive pass-bands have been used, in addition to high-pass, band-pass, and low-pass filters.

   Rhythm may be imposed easily on musical sound structures by means of ring modulators and tape loops. The sequence of sounds and the audio-frequency voltages picked up from a scanned tape loop are fed to the input terminals of a ring modulator. The sound is passed only when the pulses on the tape loop occur. There is also an arrangement which permits the timbre structure to be varied rhythmically with the aid of a set of octave filters. For this purpose, eight control frequencies are recorded on tape.

   Means are provided for hand-drawing the sound envelope. A gain regulating device is controlled by a photo-resistor, which is controlled in turn by the varying density of motion picture film carrying a hand-drawn pattern. The pattern is obtained by applying quick-drying varnish. For short reverberation times a real reverberation chamber is used. For discrete echoes a magnetic-tape echo is used.
3) Four synchronized tracks are provided by two tape layers side-by-side, with a synchronized drive driving perforated magnetic tape. The material on three recorded tracks is transferred to the fourth, the three tracks then being erased so that an arbitrary number of layers can be combined. Eighteen loudspeakers along the sides and

[61] Enkel, *loc. cit.*

ends of the studio are divided up into three separate groups, each being connected to one reproducing channel of the four-track tape recorder. In this way an arrangement of three sound sources in space is obtained. A considerable increase in the emotional response evoked by the sound patterns can be attained by changing the apparent distance and volume of the sound sources at the recording stage on the tape by electroacoustic means. The fourth track is used for control functions similar to those performed by the tape loop used for obtaining rhythmic effects.

The presentation and reproduction of sounds and noises is greatly facilitated by their clear characterization. A ring modulator in combination with a reflecting galvanometer having a build-up time of one second, and hence a resolving power of one cps, proved very useful. The arrangement yields high selectivity up to a fraction of one cps.

The music of the Cologne group demonstrates in a striking way the tremendous range of new sound possibilities provided by electronic techniques. Multiplicative mixture of sounds is an example.[10] When two sinusoidal voltages are mixed in suitable apparatus such as a ring modulator, the original frequencies are replaced by the sum and difference frequencies. If a complex tone is kept constantly at a fundamental frequency of, say, 300 cps, while a sinusoidal tone traverses all the frequencies starting from zero in glissando, the time-frequency spectrum of the product of the two oscillations shows the structure of Fig. 20. The

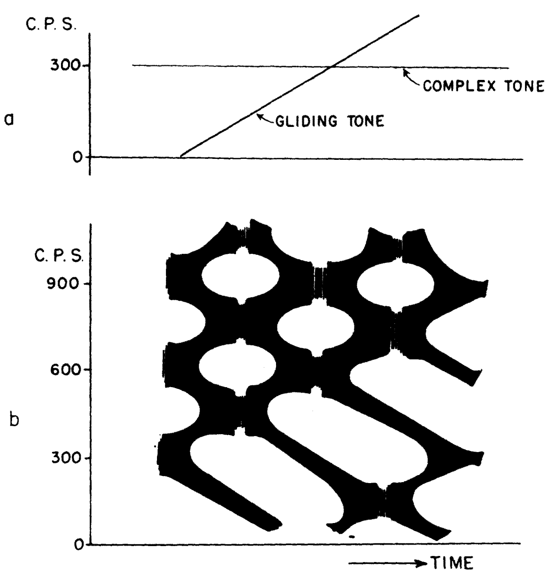

Fig. 20—*b* is a sound spectrogram of a complex tone of 300 cps. mixed multiplicatively with a sinusoidal gliding tone, starting from zero and varying with time, as shown at *a*. (After Meyer-Eppler.)

more rapidly the glissando is performed, the more closely will the result approach a noise. By mixing noise with a sliding tone multiplicatively, a sliding or howling noise with two spectral regions is obtained.

Schoenberg's idea of relating different timbres in a manner similar to that in which the notes of a melody are related, and Webern's permutations of sounds, lead directly to the shaping of sounds by the grouping of sinusoidal tones which is being investigated by the Cologne group. Stockhausen[62] described the first composition for sinusoidal tones which was produced at the Electronic Music Studio at Cologne. No ready-composed spectra such as produced by the Melochord or Trautonium were used at all. Simple frequency and amplitude conditions of the musical construction were set up, the nature of the sound following as a result.

The control of the composer or arranger over the sound is so much greater in the case of electronic music, that conventional musical notation is inadequate.[63] The logical way to describe electronic sound might be in the form of an acoustic representation; that is, the complete description of all the sound processes. A glance at the history of our present musical notation, however, suggests the importance of description by means of symbols rather than the complete representation. In setting up a new notation, care must of course be taken to make it as broad and as scientific as possible, rather than rational according to some previously known musical system, as is our conventional notation.

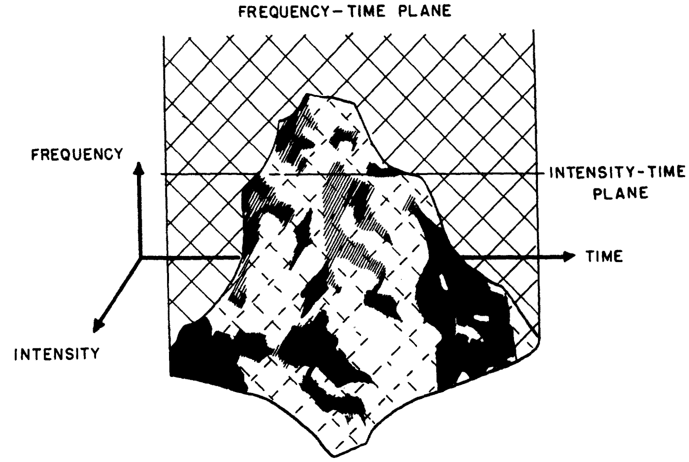

Fig. 21—Representation of an arbitrary sound. (After Eimert, Enkel and Stockhausen.)

Acoustic phenomena can be represented by a three-dimensional diagram employing the coordinates: frequency, intensity, and time. Sound processes which have time limitations are depicted as solids. It is possible to draw these solids using the rules of analytical geometry, by projecting them on various planes. For this purpose the solid representing the sound is cut into sections in such a way that all the details required for such a process are recognizable (see Fig. 21). In almost all cases it is sufficient for this purpose to have sections which depict the frequency-time plane and the gain-time plane. The number of sectional areas depends

[62] Stockhausen, *loc. cit.*
[63] Eimert, Enkel, and Stockhausen, *loc. cit.*

upon the structure of the sounds and noises, and must be great enough so that a reconstruction of the sound event is possible on the basis of the diagrammatic elements. It has been found useful for this purpose in each case to set up a frequency-time plane and the corresponding gain-time plane. The sound processes occurring in these planes can be described with the aid of a few simple symbols.

The Electronic Music Studio at Cologne characterizes acoustic properties in the following way.

Pitch and duration are plotted in the frequency-time plane, the exact amount of the frequency and the gain to be written above the line representing the partial (see Fig. 22). So that the entire auditory range can be covered by a single scale, the frequency range involved in each case is indicated by a factor placed in front.

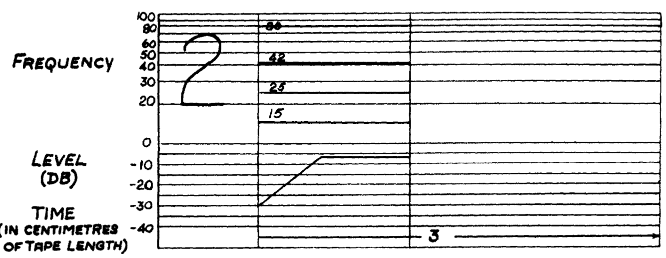

Fig. 22—Notation used by the Studio for Electronic Music at Cologne for characterizing sounds to be produced by electronic techniques. (After Eimert, Enkel and Stockhausen.)

The dynamic character of the sound event is obtained from the gain diagram. As seen in the example, the fade-out conditions are presented by a falling dashed line. For reasons which derive directly from the method of production, the time axis is graduated directly into lengths of magnetic tape referred to a tape speed of 66.2 centimeters per second.

If two sounds are to be modulated one by the other, the partial distribution of the original sounds are set down as above. This, of course, is done in two systems arranged one above the other. The kind of modulator to be employed is indicated in writing between the two systems. If a colored noise band of given width is required, this can be represented by two frequency lines joined at the beginning and at the end, showing the band limits. The dynamic characteristic, as usual, is indicated on the gain plane. If the frequency band has been compressed or expanded, the partial distribution of the sound to be compressed or expanded, as described earlier, is entered in the usual way and the expansion or compression value is indicated on the time scale; for example, the number "3" indicates a threefold expansion of the original sounds, while "$\frac{1}{4}$" means compression down to one-fourth of the original sound. By combining the above examples, and from the composition in a given case, a sufficient number of symbols may be assembled easily.

A score which uses only sinusoidal tones can be realized from the graphical instructions in the way that a manufactured article is produced from a drawing; that is, it can be executed by the technician. In other cases—for the complex sounds—the composer must specify the type of tone desired.

The notation used by the Cologne Studio may be compared with a system shown in Fig. 23, which is being experimented with by the Musique Concrète group.[54] Two staffs resembling those used in conventional music notation are used. Distance from the origin represents time. The melodic staff represents pitch in the conventional way. The character of the attack, the sustained portion, and the decay, are represented conventionally by appropriate signs. The dynamic staff may be effected by a clef sign of which the role is analogous to the clef sign in the melodic staff, and which refers to the vertical scale of the symbolic representation. In Fig. 23 the figure "30 db" indicates the range, and "0 db" indicates the level. Timbre is defined by a code where the large families are identified by letters placed at the start of the notation of the sound object being considered, for example, the letters "KZ" in Fig. 23.

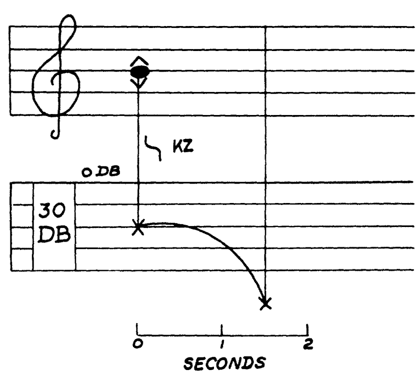

Fig. 23—Experimental notation used by the Musique Concrète Group. (After Poullin.)

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