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THE APPLICATION OF ELECTRONICS TO THE PIANO

By
Benjamin F. Meissner

INTRODUCTION

The music of Nature, in her rippling brooks, her sighing breezes, her crashing surfs or howling gales, is as old as earth itself; the rhythm of electrons, of solar systems and galaxies proceeded from the beginning, if any there was, and goes on and on to the end -- if any there be. Of man-made music, the human voice is without doubt the oldest instrument of them all. Whether the twanged bow string, the wind-blown reed, the fall of a stick or stone, or the thump of a tom-tom came next in instrumental music, no one really knows. All have been handed down through the ages, with a new touch now and then, and all are to be seen in the modern orchestra. There we find plucked strings, bowed strings, struck strings; wind instruments of wood and brass; percussion instruments of stretched skin, tuned bars of wood and steel; untuned cymbals and gongs.

In the great music of large orchestras we find them all weaving together in a magnificent moving tapestry their variegated colors and harmonies and rhythms. Here, like actors in a play, whether sweet or blatant, dull or grotesque, soothing or harsh, agile or ponderous, they enact their parts on the musical stage.

Of all these instruments, there are some much more expressive than others, capable of a wider range of tone color, or character, or power, and thus better able to portray a wider range of mood or feeling. The violin family, for example, is extremely expressive; the artist has a degree of intimacy with it perhaps unequalled in any other instrument. He has control of pitch, power, duration, and timbre also, to a considerable extent; he can start or stop a tone, pass from one to another, and from one power to another, pluck or bow his strings in many different ways. He can produce tremolo, glissando or vibrato effects; he can even play two tones at once --- thus exceeding in this respect the abilities of the human voice.

Berlioz, discussing the great value of the bowed strings in an orchestra, says: "From them is evolved the greatest power of expression and an incontestable variety of qualities of tone; violins, particularly, are capable of a host of apparently inconsistent shades of expression. They possess, as a whole, force, lightness, grace; accents, both gloomy and gay; thought and passion. The only point is to know how to make them speak."

However, as Berlioz suggests, this very intimacy between the artist and his instrument makes it a very difficult one to play well. No instrument can sound so unpleasant as a violin or cello when inexpertly played. Further, their inability to sound more than two tones together is a severe limitation for unaccompanied performance. In melody they are superbly versatile; in harmony they are severely limited. The difficulties of bowing and fingering, for quality and pitch control of string instruments, was met by the introduction of instruments with many strings, like the harp and cymballum. Here the pitch intervals were exactly predetermined by tuning one string for each pitch, and the tone quality was also largely predetermined by design characteristics. Later, keyboards and actions were introduced which provided an easier playing technique. A great variety of these keyboard string instruments were introduced, a goodly collection of which may be found at the Metropolitan Museum in New York. Probably the best collection in the world is at the Deutches Museum in Munich.

The earliest string instruments with keyboards used the plucking or scraping type of action mechanism. Of these the Clavichord and Spinet came into extensive use. The more elaborate Harpsichord followed with multipedal control, for octave shifting - coupling arrangements, etc. These instruments used very small strings at relatively low tension, as in zithers, harps, etc. Their tones may be characterized as thin, delicate, and low in power. Dynamic control was not possible.

THE PIANO

When, in the year 1709, the Italian, Cristofori, invented the hammer action, a greatly superior control was provided, enabling the player to regulate tone power by the strength of key blow. The Italians and French called this instrument a "pianoforte," meaning soft-loud; the Germans called it a "Hammer Klavier."

The history of the instruments which preceded the piano shows plainly that the invention of the hammer action was merely the culmination of a long series of efforts on the part of many great craftsmen through three centuries, looking towards the production of a musical stringed instrument capable of doing for domestic use what the organ had always done in the church, namely, to furnish complete command over all existing resources of harmony as well as melody. I may add that the modern organ, and to a lesser extent, the piano, do a great deal more than this. While the piano has no true sostenuto like the organ, it does provide individual tone power control which organs do not have. The "touch-responsive" piano action greatly expands the player's control. The organist, however, has control of a great variety of tone colors, available at the touch of a stop, which he can use singly or in combination, by couplers, or by use of several keyboards. This is the real source of the beauty of organ music; without changes in registration, its performance becomes quite monotonous. The organist also has the swell pedal for mass power control over all tones together; this compensates to some degree for his lack of power control over individual tones provided by Cristofori for the pianist. The piano's touch-responsive keyboard does a great deal more than provide piano to forte control of volume. It provides the very important change of tone quality with volume possessed by all of the very expressive instruments, such as the bowed string types, or the human voice. These, when played piano, are soothing, sonorous, pleasing. At forte they become strident, even unpleasant. The physicist would describe this as a shift of energy from the lower to the higher partials. The radio engineer would compare it to overloading an amplifying tube.

The touch responsive piano, therefore, provides simultaneous, not separate, control of tone power and quality together, a decided improvement over the organ, which has control over power alone, and that only a mass control. The piano, particularly in the lower and middle registers, like the lion, will sigh or snarl or shriek, depending on whether you pet or punch or pound it.

COMPARISON OF PIANO WITH ITS PREDECESSORS

In Figure 1 are shown the various harmonic compositions of the piano and some of its predecessors. In all of these spectrograms the fundamental frequency was 128 cycles, an octave below middle C. The amplitudes have all been reduced to a common level so that

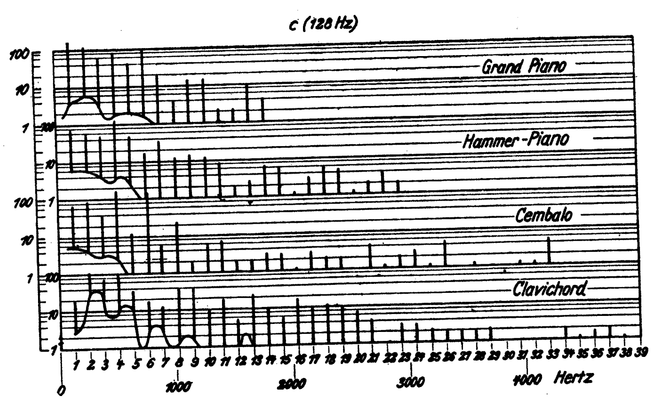


Fig. 1. Spectra of older pianoforte-like instruments.

FIG. 1
SPECTROGRAMS SHOWING LINE AND CONTINUOUS SPECTRA OF THE PIANO AND ITS PREDECESSORS.

this factor does not appear. The Clavichord, with a combined striking and scraping action mechanism, exhibits the thinnest, most delicate tone; today however, it might be termed "tinny." Next, the Cembalo, in the spinet-harpsichord family, with quill-plucked strings, has a tone less bright or thin than the Clavichord. The Hammer-Klavier, such as Chopin and Beethoven used a hundred years ago, gave a tone somewhat duller or darker still in quality. The modern grand tone is still darker, less strident or thin than the others.

In Figure 2 are shown seven spectrograms giving the harmonic composition of a grand piano on seven tones in octave intervals; notice the increase in harmonic richness from high to low tones; notice also the strong, continuous, or noise spectrums, shown by the continuous lines, produced by the hammer blow at the higher frequencies.

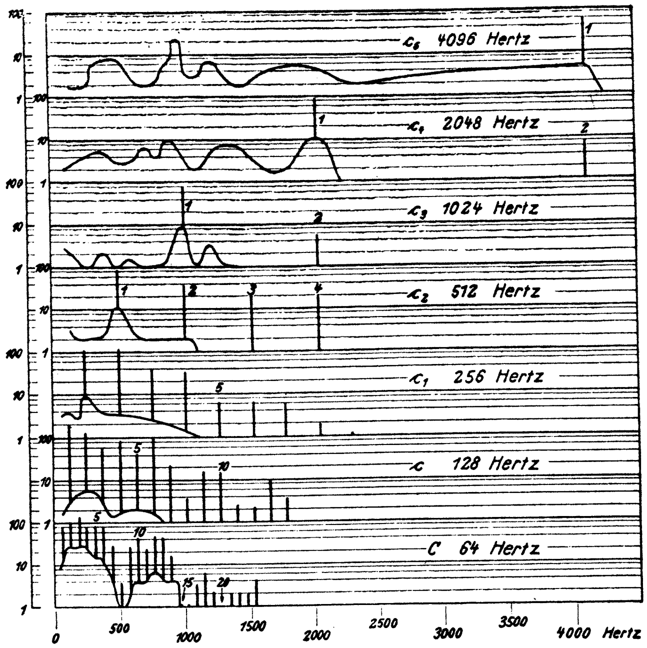


Fig. 2. Spectra of a grand pianoforte.

FIG. 2
SPECTRA OF PIANO TONES IN OCTAVE INTERVALS.

EFFECT OF KEY BLOW

In Figure 3, I show the influence, on harmonic composition, of hammer velocity, as governed by strength of key blow, on the modern grand piano.

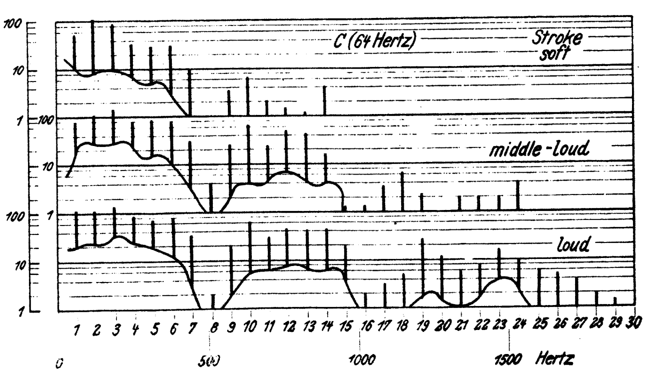


Fig. 3. Influence of the strength of stroke upon the spectrum.

FIG. 3
VARIATION OF HARMONIC COMPOSITION OF A PIANO TONE WITH FORCE OF KEY BLOW.

The top spectrum was produced playing softly, the middle, moderately loud; the bottom very loudly. Notice how the partials come in at higher and higher frequencies with increasing key blow; not shown again is the accompanying increase in general loudness, all three spectrograms having been reduced to a common amplitude level. The curves show the continuous frequency bands and relative amplitudes of the noises produced by the hammer blow, and the broad resonance effects of the soundboard. These sounds are induced in the soundboard by the shock excitation of the hammer blow and continue, with quite rapid damping, (fading) after the shock has passed. Those partials lying within these resonant ranges are, of course, amplified, as shown by their greater amplitudes at the peaks of the continuous curves.

MODERN PIANOS NOT MUCH IMPROVED

The piano of today is, with improvements in detail only, the pianoforte of a hundred years ago; no really significant change in principle has been made. Chief among the improvements is the perfection of steel wire with regard to tensile strength. Higher and higher tensile strengths have provided two significant improvements. First, the change from stretched string plus bar-like vibrational characteristics, to almost wholly string characteristics, and thus gradually wiping out the inharmonic partials of the former; and second, the increase of storage capacity for kinetic energy, which permits transfer of more and more of the energy imparted by the key blow, through the action and hammer, to the string. This improves both the beauty and the power of the tone. It permits, according to the choice of string to soundboard coupling, either a much louder tone, a much longer tone, or, as utilized in modern instruments, a moderate increase in both loudness and duration.

ADVANTAGES OF PIANO OVER OTHER INSTRUMENTS

To summarize then, the great popularity of the piano is due, first, to the ease with which perfect pitch intervals and perfect tone quality may be secured. The veriest tyro can play a series of pitch intervals just as precisely as the greatest artist; second, without the slightest difficulty, he can produce just as beautiful a quality in each tone; third, he can control the power and quality of each tone with the touch-responsive string vibrating mechanism; fourth, he can play, unaided by others, harmony as well as melody; this factor alone accounts for the great popularity of the piano.

While the piano is, undoubtedly, a great and beautiful musical instrument, there are many signs of long-desired improvements in various directions. Chief among these is control over the character or qualities of its tone.

TONE CHARACTER

Tone character, that is, the characteristics which so markedly distinguish the tones of different musical instruments, one from the other, may be separated into several groups. The most important of these are:-

1) *Harmonic Composition:* This may be expressed as the amplitude ratios of the various harmonically related partial or component simple tones in the complex sound. It determines tone quality or timbre, as was illustrated in Figure 1. In many instruments this changes with the amplitude of the driving force. This was shown for the piano in Figure 3. It may also vary during the tone production at constant amplitude in some instruments, depending on the manner of excitation, as in the bowed strings. In the piano it changes constantly from beginning to end of the tone. There may also be inharmonically related partial tones present --- as in bells, or bars held at one end, or strings under insufficient tension.

2) *Dynamic Characteristics:* This refers to the power characteristics of the tone generally, but also more particularly to its relative power from beginning to end. The clarinet or oboe stops of a great organ may produce very close approximations to the true timbres of those instruments, but there is a very marked difference in power. But, more significantly, the shape of the tone wave train envelope may take on many different variations and result in many different tone characters. For example, the chief difference in character between a piano tone and that of a saxophone or clarinet is that the former starts loud and dies away rapidly, while the latter starts at zero, builds up rapidly, and continues, ordinarily at uniform loudness, except as modified by the player's blowing technique. In Figure 4 are shown two oscillograms representing these two types of dynamic inception character.

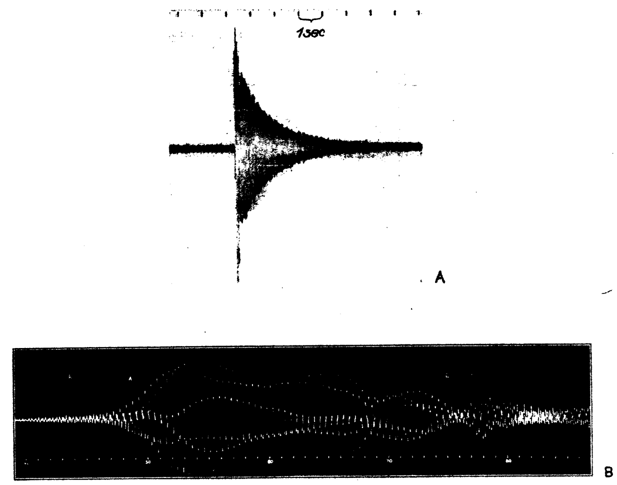


FIG. 4
ENVELOPE SHAPE IS A STRONG DETERMINANT OF TONE CHARACTER. (A) PIANO TONE; (B) WIND INSTRUMENT TONE.

A shows a piano tone with abrupt inception and immediate logarithmic decay; this character is typical of all percussion and plucked string tones. *B* shows the gradual inception of the letter *a* as spoken in the name Raleigh; this is typical of all wind instruments, of which the human voice is a perfect example. A banjo tone may have very nearly the same harmonic composition as a piano tone but differs very noticeably from it because of a much higher rate of damping, that is, rate of tone power diminution. The early phonograph records of pianos sounded a great deal like banjos and guitars principally because the high audibility threshold of the phonographic apparatus brought out only that part of the piano tone occuring in the first few seconds, and thus greatly increasing its apparent damping; and also, of course, because of the omission principally, of lower frequencies. The dynamic envelopes of the many partials may all have different forms. For example, in the piano, the higher partials die out much quicker than the lower.

3) *Incidental Noises:* In the percussion and plucked string instruments, in addition to the always falling dynamic characteristic of the tone, there are also significant incidental noises at the beginning of the tone. In bowed string tones, the bow-scrape noises are always present more or less and are as much a part of the tone character as the distribution of energy in its component partials, or as the shape of its dynamic envelope. In Figure 5, I show an oscillogram of a violin tone. Here is plainly a high frequency tone, superimposed upon one of low frequency. Clearly, the low frequency is the rate at which the string clings to and releases from the bow. The high frequency is that of the string itself. Both, of course, are complex in composition.

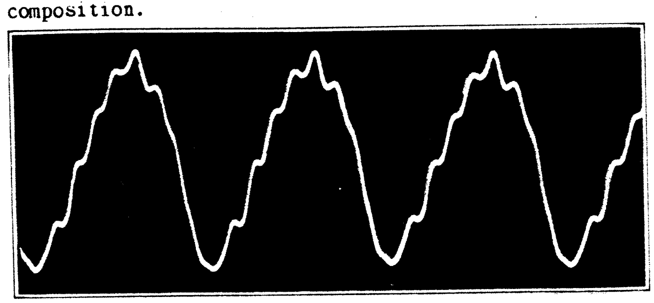


FIG. 5
OSCILLOGRAM OF A VIOLIN TONE

CHANGES IN FREQUENCY AND AMPLITUDE

4) There are also other distinguishing characteristics such as tremolo and vibrato, known to the radio engineer respectively as frequency and amplitude modulation. Another is frequency or pitch range; with regard to the latter, a flute and a tuba might have very similar characteristics in every respect yet no one could fail to distinguish them owing to their very different frequency ranges.

These are the principal elements found in the make up of tone character. I will make no attempt to break them down into finer subdivisions, combinations or sub-combinations.

With such a set of ingredients it is possible to set together musical tones of practically any desired character; with suitable control over the utterances of these characters, it is further possible to construct and correlate them in the various melodic, harmonic, dynamic, and rhythmic patterns, which we call Music.

DESIRABLE PIANO IMPROVEMENTS

As I have previously stated, there are many directions in which the piano may be greatly improved. In the first place, its single type of tone quality, when compared with the many tone qualities of the organ or the orchestra, presents a very great limitation; secondly, the piano is always a percussion instrument; its tone always starts with a crash of percussion transients and then dies rather rapidly away, logarithmic fashion, with more or less continuous change in harmonic composition. The strong percussion noise and rapid fading out is especially noticeable in the upper registers. In all the wind instruments, and, within control, on the bowed string instruments, the tone starts with low amplitude and quickly builds up to normal. Here is a complete reversal of the dynamic inception characteristic of the piano tone; and this reversal, even without the percussion transients, is sufficient to produce, out of a given harmonic composition, two tones of decidedly different character. A very great improvement, then, would be provided with the ability to control the dynamic inception characteristic of the tone, thus producing tones characteristic of percussion or of wind instruments at will.

Just as important as the dynamic *in*ception of the tone, is its dynamic nature after inception. The piano always has a falling tone power characteristic while the organ quickly reaches a steady state and holds it so long as the key is held. Both may be brought to an end with a rapid, though not sharp, falling characteristic by key release. In the piano the damper acts quickly though not instantaneously. In the organ and other wind instruments the vibrating air column continues apace until its stored energy also is dissipated. The ability to predetermine the tone damping, that is, the ability to make it sustain indefinitely, without damping, and to provide any desired degree of damping, constitutes also a very important control of tone character. While I have not incorporated in this instrument arrangements for producing indefinitely sustainable or undamped tones, that, with some increased complication, is possible. However, I do have arrangements for increasing the normally quite low damping rate of the tones.

The ability to inject certain incidental noises, to provide tremolo and vibrato effects, at will, further adds to our control over tone character.

Here then you have my conception of the advantages, the limitations, and the very desirable improvements for the most popular of all home musical instruments, the piano. To keep the most important advantages, to efface the worst limitations, and to add the best improvements then, was the problem which, some years ago, I set myself to solve. The instrument to be demonstrated later, represents in a general way the results of my efforts to date. It is not a commercial design, nor does it embody all of the many improvements developed in my laboratory. My efforts thus far have been devoted rather to an exploration of the possibilities and the development of a variety of solutions for the many individual problems than to a combination of them suitable for commerce. It *is* an operating model, in which some very significant improvements are included; in which some, perhaps equally important, are not yet included. While some of you might be interested in following the course of its technical development, that, obviously, time does not permit.

THE ELECTRONIC PIANO

Now I will proceed with a technical explanation of the operating principles and the instrument itself. What you see here in Figure 6 is essentially although not quite a piano. It has a conventional body or case,

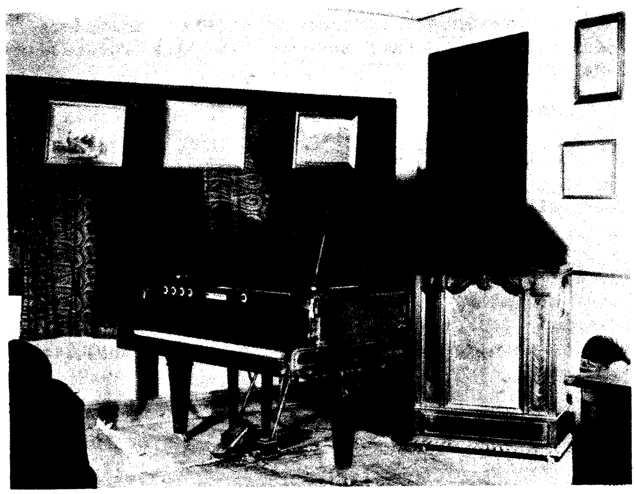


FIG. 6
THE MIESSNER ELECTRONIC PIANO

an inner iron plate strung with strings over a vibratile bridge; tuning pins for tuning the strings; a keyboard and hammer and damper action for selectively setting the strings into vibration, and for stopping that vibration. However, it has undergone some rather important changes. You note a number of control knobs and buttons above the keyboard; a swell pedal in place of the unicorde or soft pedal; an additional cabinet containing an amplifier and reproducers.

In Figure 7, showing the interior of the piano, you

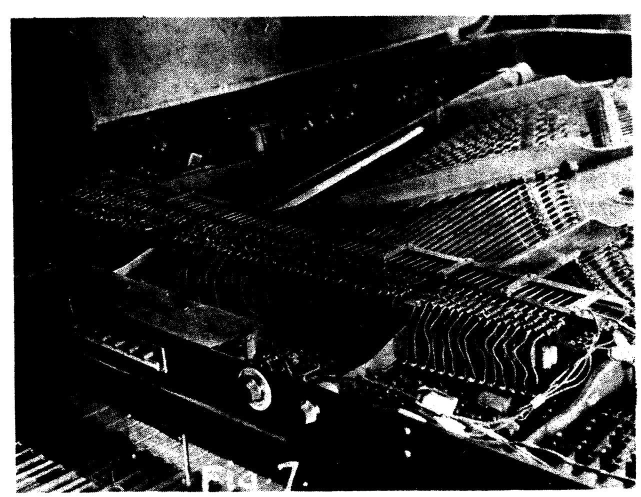


FIG. 7
INTERIOR OF ELECTRONIC PIANO

see many more changes. You see through the strings, in the right middle of the picture, that the soundboard has been cut away, leaving the reinforcing ribs; you see a small amplifier, and additional apparatus, which I will later describe more in detail. The soundboard has been cut away from its supporting ribs in order to retain the benefits of inter-string coupling, and to greatly reduce their coupling, through the soundboard, to the atmosphere. While often called a resonator the soundboard is, of course, really no such thing. It is simply a coupling device, with its action only very broadly resonant. It is certainly no more a resonator than the diaphragm of a loud speaker. The piano string has altogether too small a surface for efficient transfer of its vibratory energy into motions of the surrounding air. This purely mechanical soundboard device is therefore used between the two, and incidentally with a step-down action of about 1,000 to 1, so that the large motion of the small surface string is converted into a small motion of the large soundboard.

Since we wish to use a different, far more flexible and controllable system for translating string vibrations into sound waves, and since we wish practically complete control of all translation, we have cut away the soundboard. If this had not been done many of the effects we wish to secure would be blanketed by the normal piano sound sent out from this board. Further, the small residual sound emanating from the coupling between air and strings and ribs, and other vibratory parts of the structure as a whole, is absorbed by internal padding, or hindered in its escape by closed bottom and top. A careful, wholly new design would permit a still greater reduction in this purely mechanico-acoustic coupling. On the other hand, this weak direct sound is useful for certain tonal effects or for practise at low volume.

These changes are merely preparatory to the introduction of the new electro-acoustic translation system. They have not materially affected the rest of the instrument, except to reduce the rate at which the string declines in its vibration amplitude, because of the diminished hysterisis and radiation losses of the vibratile system.

MECHANICO-ELECTRO TRANSLATING SYSTEMS

There are numerous principles upon which a mechanico-electro vibration-conversion system may be based, for replacement of the soundboard. Among these may be mentioned modulations by the vibrating string of a magnetic or an electrostatic field, or a resistance; or operation of a piezo-electric, electro dynamic, magnetostriction, or other such device. In Figure 8, I show schematic representations of these string vibration conversion devices.

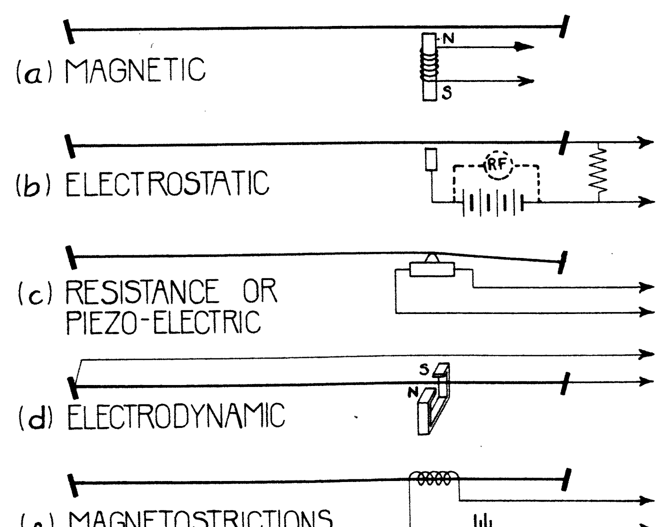


Fig. 8
TYPES OF TRANSLATING APPARATUS.

In (a) the magnetic field of the magnet threading the coil is modulated by vibrations of the steel string, thus producing a voltage vibration in the coil; if the string is magnetized the coil core need not be. In (b) the string vibration modulates its capacity to the pick-up conductor, and thus modulates either a steady voltage or a high frequency current. In (c) the string bears down with some pressure on a resistance or piezo-electric device and, as it vibrates, this pressure is modulated, thus varying the resistance, or generating a voltage in the piezo crystal. In (d) the string is a conductor vibrating in a magnetic field and thus has voltage generated in itself. In (e) the string is magnetized and its longitudinal extensions so disturb its magnetic field that a voltage is generated in the coil.

Of these the electrostatic principle appears simplest and most generally useful for the particular requirements at hand. As applied to my piano, a thin, narrow conductor is mounted near and underneath the strings, on a well-insulated support, as shown in Figure 9. You see three of these, a, b and c. Its insulation resistance should be of the order of 100 meg ohms. In general it is just far enough from the strings

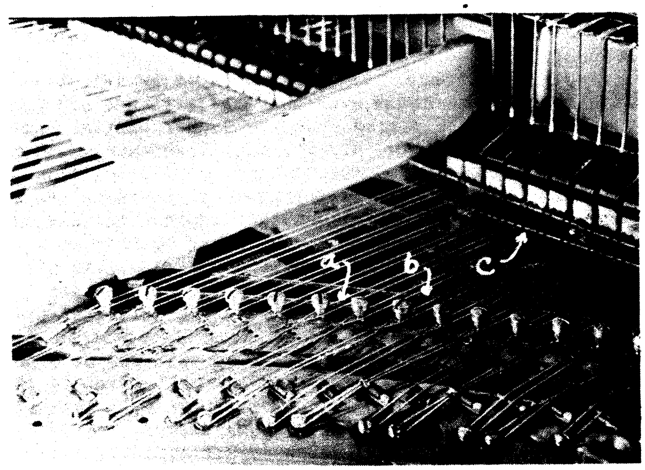


FIG. 9
DETAILS OF PICKUPS, VOICING SCREWS, AND STRING INSULATION

to prevent contact on the most violent vibrations which the strings undergo. When a voltage is applied thru a high resistance, between the strings and this conductor, vibratory variation of the distance modulates the capacity; since the total charge is fixed, by the high resistance, except for extremely low frequency modulations, the voltage across the capacity is modulated also; in its electrical operation here it resembles the familiar condenser microphone, or perhaps numerous condenser microphones connected in parallel, each with a tuned diaphragm. Note the cut-away soundboard again, the insulation between strings and plate, the voicing screws on the bridge for lowering or raising the strings with respect to the pick-ups.

TYPES AND ARRANGEMENT OF ELECTROSTATIC PICKUPS

The shape, the position, and manner of mounting of this "pick-up" are of considerable importance. In Figure 10, I show some of these possible arrangements. In general, it should be very narrow along the string, unless very high partials are not to be translated. If, for example, it were as wide as the string is long, only the fundamental and a few low-numbered, odd partials would be translated.

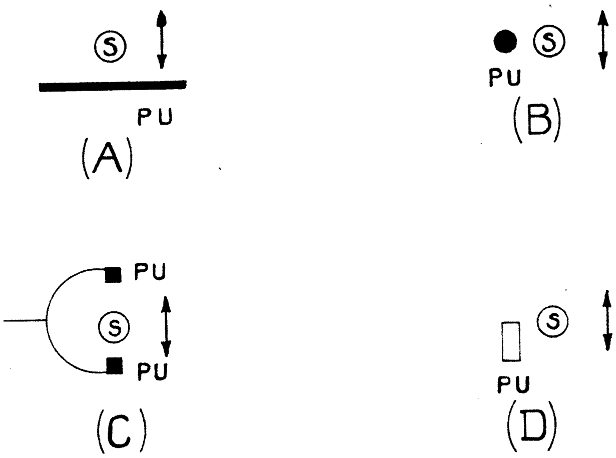


Fig. 10

ELECTROSTATIC PICKUP TYPES.

The depth of the conductor perpendicularly to the string axis, as well as the separation, affects the shape of the translated voltage wave form. The position of the pick-up along the string will affect the harmonic composition of the translated vibration. If at the string middle, only odd-numbered partials will translate, because there the even partials all have nodes of amplitude. At the string ends the higher partials have more nearly equal, or strong, amplitudes compared to the lower; this is reversed toward the mid position. A shows our normal pick-up. If two pick-ups be set in complementary positions about the middle of the string, either the odd or the even partials may be made to neutralize, depending on the relative phases of the pick-up outputs. If pick-ups be placed alongside a string, as shown at B, strong frequency-doubling action is provided; assymetric pick-up, providing a sometimes desirable distortion, is secured by two pick-ups on opposite sides of the string as shown at C; here, if the two spacings are equal, all frequencies will again be doubled; if assymetric, varying degrees of non-linearity in translation may be secured; if a single pick-up be placed obliquely to one side, as indicated at D, a combination of simple and doubling action occurs.

Another matter is concerned with the rigidity of the pick-up device. It may introduce spurious, unwanted frequencies or noises, if it, itself, can vibrate, or if it is attached to some part of the instrument which vibrates differently than the string-bridge system.

I have found that, for general purposes, a pick-up conductor, consisting of flat, one-sixteenth inch, copper braid, glued to the narrow side of a strip of bakelite one-eighth inch thick by one-half inch wide, and securely fastened, conductor-side up, to each of the wooden ribs, is a satisfactory type and mounting. This selection has, however, been rather largely influenced by our desire to secure, among other types of tone, one closely resembling that of the piano.

TONE QUALITY CONTROL BY SEVERAL PICKUPS

A plurality of pick-ups of different form, position along, or position around the string, may be used singly or in combination, still further to change the harmonic composition of the translated wave from that of the string itself. An over-all control, known in radio as a tone control, permitting tipping, about some central region, of the frequency-gain characteristic of the amplifier, provides still further control of harmonic composition. The possibilities for control of harmonic composition are thus seen to be almost limitless, at least for change of the harmonic structure provided by the struck string; and I may say that the string has a wealth of such material to work with. The string itself is certainly a simple, cheap, and rugged source of this harmonic material. Cristofori's mechanism for control of its vibration, while not simple, is certainly rugged and time-tested. In the present instrument, all of these possibilities for tone quality control are not included, and it is possible that a better selection and arrangement might have been made. However, this selected arrangement is simple and effective.

Three pick-ups, of the type previously described and already shown, are used. One of these is very close to the back end of the string, at about one-sixteenth string length, where the high partials are prominent; another is placed at about the one-sixth-from-back position; a third is placed in a position about one-third from the front end. To compensate to some degree for the irregular frequency-response characteristics of loud speakers, the strings are provided with individual pick-up spacing adjustment screws; these are mounted on the bridge and raise or lower the individual strings with respect to the pick-up strip. This adjustment operates much more effectively for the pick-up nearest the bridge than for the other two. A more perfect, though more complicated arrangement would provide fixed position strings and adjustable pick-ups for each string on each bar.

CIRCUITS OF THE ELECTRONIC PIANO

Before proceeding to detailed description of the various elements of the electronic system in the piano, I show, in Figure 11, the chief component parts and their arrangement. The piano key, K, thru the action, A, hammer, H, and damper, D, controls the mechanical vibrations of the string, S. The string charging circuits, coöperating with switching devices in the piano action --- control the polarizing charges on the strings.

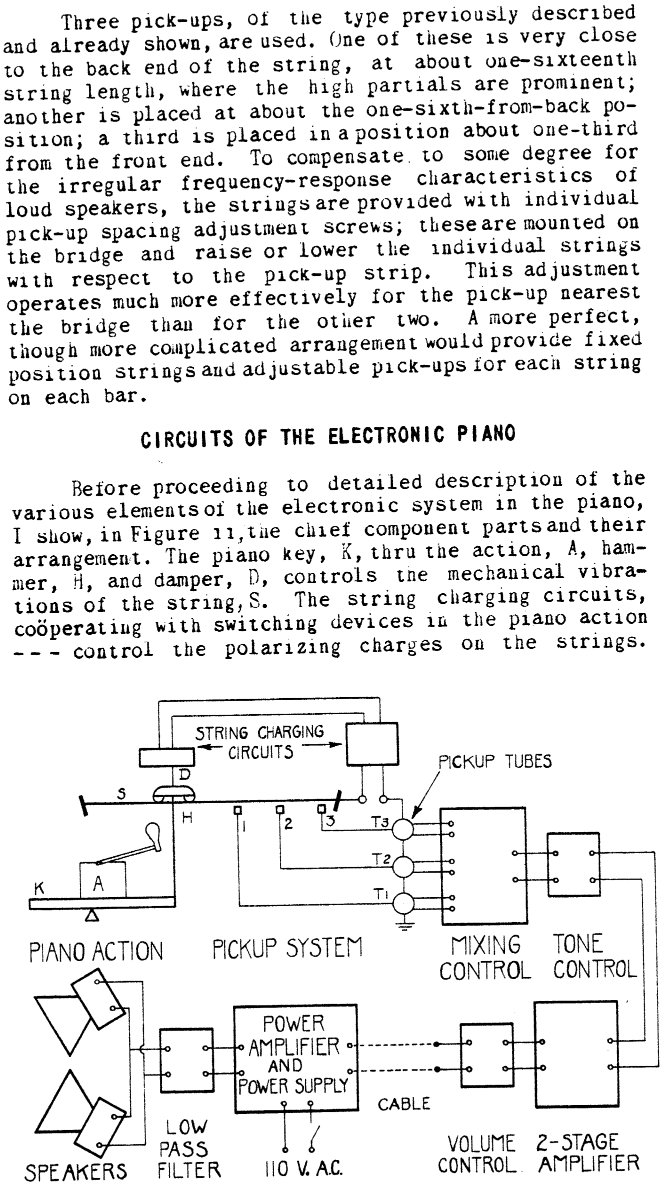


Fig. 11 GENERAL ARRANGEMENT OF ELECTRONIC PIANO CIRCUITS.

Pick-ups 1, 2 and 3, feed into individual pre-amplifier tubes T_1, T_2 and T_3 respectively. These tubes feed into a mixing circuit wherein the relative amplitudes of the amplified pick-up voltages may be varied in aiding or bucking phases. Following this is the tone control circuit for adjusting the frequency-amplification characteristic of the first stage of the following two stage amplifier. The second stage of this amplifier is a push-pull driver for the power amplifier. Next we have a volume control operated by a swell pedal. All of the preceding apparatus is in the piano. The remaining power amplifier, power supply, low-pass filter and reproducers, are in a separate cabinet, connected to the piano by a multicable and plug.

OPERATION OF MIXING CIRCUIT

Referring now to Figure 12, the three pick-up strips connect to the grids respectively of three amplifier tubes. These tubes have output transformers 14, 14a and 14b, with parallel mid-tapped potentio-meters, all connected in a series mixing circuit so that any desired amplitude in either aiding or opposing phase may be used from either of the three pick-up tubes. This mixing circuit then feeds into a tone

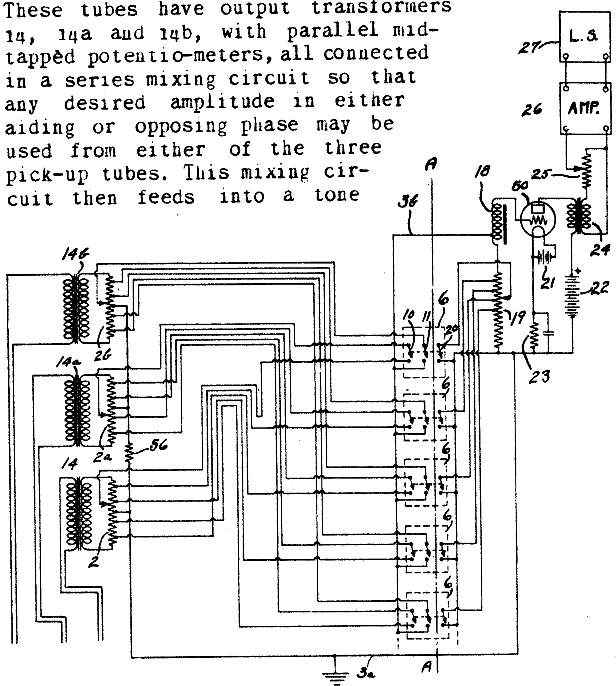


FIG. 12
TIMBRE-CONTROL CIRCUITS.

control circuit, so arranged that tipping of the voltage-frequency characteristic is provided. By means of this latter control the frequency characteristic may be made rising, flat, or falling, as desired. For these mixing and frequency-characteristic controls two interchangeable types are provided. One of these is a manual, or fine control, by continuously variable potentiometers; the other, a preselected type using multiple push-button-jack-switches and step-by-step potentiometers. Either manual or preselected control type may be switched into operation by another multipole, button-operated, jack switch. These switches are fitted with an interlocking mechanical arrangement so that only one may be set at a time; when a new button is pushed the old one releases by this single motion. A simple comparison will illustrate this arrangement perfectly. A painter may mix any desired visual hue by proportioning his three primary colors, red, yellow and blue, and then brightening or darkening it by additional use of white or black. Or he may use pre-mixed pigments in a great variety of hues. The primary acoustic color sources here are the three pick-ups; the brightening or darkening is obtained with the tone control. For delicate, in-between shades both painter and pianist would use the manual mixing method; for obtaining ordinary colors they would use the easier pre-mixed method.

To make the operation of this tone mixing system clearer, I show, in Figure 13, a schematic representation of a string vibrating with, for sake of simplicity, only three components, namely the first, or fundamental, the third, and the tenth, in amplitude ratios of, say, ten, five and two, respectively. If we place a pick-up at the string middle, A, and just beyond touching distance, it is clear that the translated amplitudes of the odd numbered first and third components will be the same respectively as in the string itself. Notice further, that the even numbered tenth does not translate at all owing to its vibrational node at that point. A

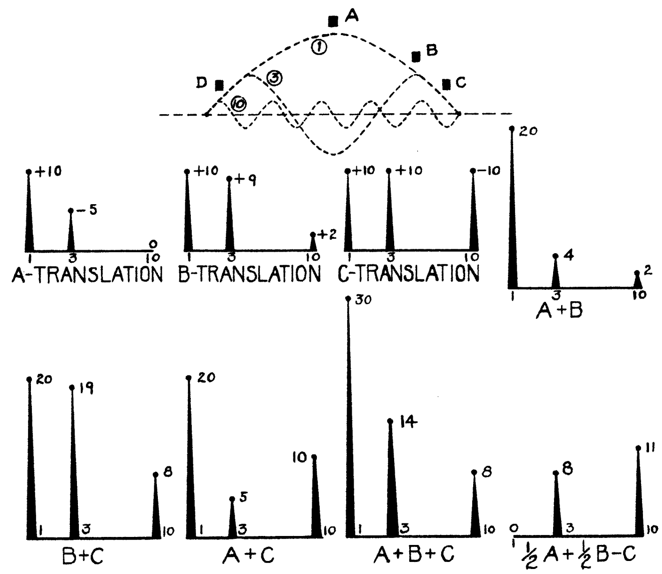


Fig. 13 STRING PARTIALS AND PICKUP SPECTROGRAMS.

pick-up at B, about one-sixth from string end, will give translated amplitude ratios of about ten, nine, and two for the three components. One at C, for the one-tenth position, gives ratios of about one, one, one. Another one-tenth position pick-up, placed on the same side of the string but at the opposite end, D, will have these same ratios but the phase of the even numbered partials will be reversed, while that of the odd will still be the same. If C and D are used in combination, with equal amplification, the odd numbered partials ten will neutralize. Such complementary-position pick-ups, no matter at what fractional string positions, may thus be used to cancel all even or all odd-numbered partials translated from a string, while a mid-point pick-up translates only odd numbered partials.

Let us see now what happens if we combine, say A with B. The fundamental component of A, with amplitude 10, and of B, with amplitude 10, aid, making partial one of amplitude 20 on our scale; the translations of the third component, however, are in reverse phase but differing amplitudes. At A it has an amplitude of minus five, while at B it is plus nine; the algebraic sum, therefore, is plus four.

The tenth partial at A is zero, and, at B, two. The same numerical and tonal results are obtainable by combining A and D. Of no consequence is the fact that the relative phase of the tenth partial to the other two would thus be reversed. This has no influence on tone quality.

If we combine B and C together, again with equal amplification, we get another spectrum, as shown in the Figure; shown also is the combined translations of A and C as well as A, B and C together.

Let us now take advantage of phase reversal and of amplitude control of the translation of A, B and C, provided in our mixing system. Take, for example, A's and B's translations at one half amplitude and of the same phase, and combine these with C's translation at full amplitude with reversed phase. We have now eliminated the fundamental altogether, and turned the amplitude distribution completely about with respect to the remaining two partials. There is an endless variety of such mixtures possible with continuously variable control over the amplitudes of the translations of several such pick-ups in different positions and with reversible phase.

OPERATION OF TONE-CONTROL CIRCUIT

But we go yet another step further by applying the control over frequency-amplification characteristic in the amplifier circuit following the mixing system.

In Figure 14, I show two extremes and one mean adjustment of the continuously variable tone control. With it any of the tone spectrums obtainable from the mixing system may be reproduced about as delivered by the latter using A; may be depressed in amplitude in the lower and elevated in the upper frequencies as in C; or may be reduced somewhat in the lower without much change in the higher frequencies as in B.

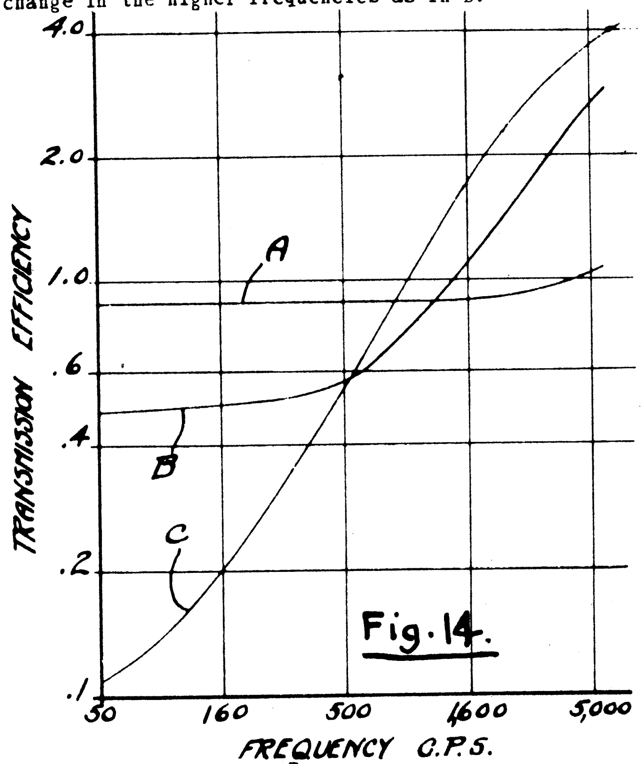


FIG. 14
CURVES FOR THREE ADJUSTMENTS OF TONE-CONTROL POTENTIOMETER

Obviously, by means of these various controls over harmonic composition, a great many varieties of tone quality may be obtained from the relatively fixed quality present in the piano string.

The output of this tone control system, as previously shown, is fed into the first common tube of the amplifier. This tube then feeds into a pair of 59 type tubes in push-pull and used as three-element tubes. Controlling this input is a master gain control potentiometer, used to set the maximum output sound power. These power-amplifier driver tubes feed into a 500 ohm matching transformer feeding into the power amplifier. In this 500 ohm line is placed a constant-impedance attenuator controlled by a foot pedal. With this the pianist has instantaneous control of tone power and with it numerous important musical effects may be secured.

I show the power amplifier, speakers, power supply, etc., in Figure 15. The power amplifier uses push-pull 845 tubes in a Class A circuit. Between these tubes and the speakers, in addition to a matching transformer, is a low pass filter, cutting off at about 6,000 cycles. This filter does not appreciably affect the desired tone quality, but it very greatly reduces those troublesome and unpleasant noises introduced by an amplifier at even subnormal output power. Two self-excited speakers are used, with crossed sound beams, for better distribution of the high frequency portion of the output sound spectrum. The entire amplifier is a.c. operated.

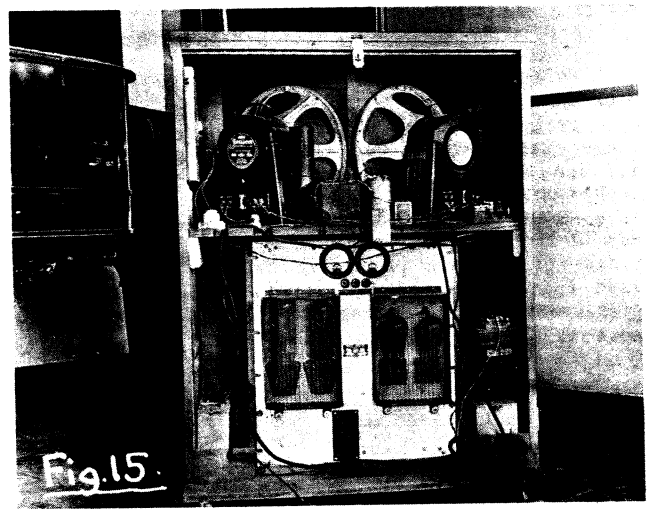
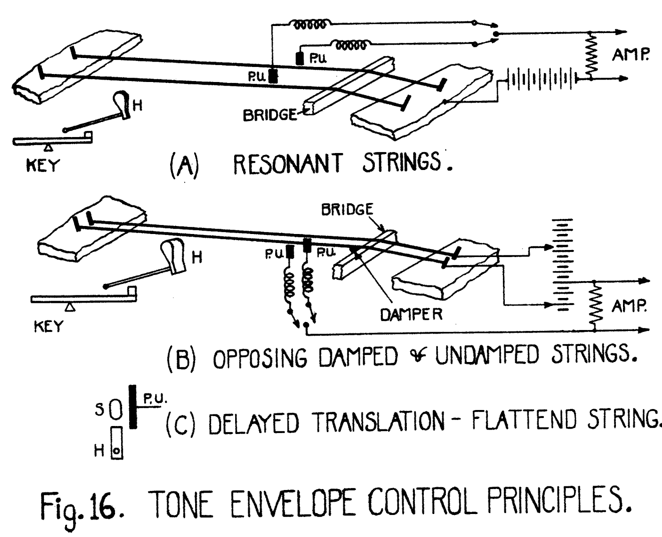


FIG. 15
POWER AMPLIFIER, POWER SUPPLY, SPEAKERS, ETC., IN SEPARATE CABINET.

That part of it up to the power amplifier is included in the piano as a pre-amplifier, the remainder is in a separate cabinet. Connection between them is made by a multiconductor cable and detachable multiple connector. The entire piano is electro-statically shielded; on the bottom by screening, and otherwise by conducting paint made of a solution of colloidal graphite.

TONE CHARACTER CONTROL BY ENVELOPE SHAPE

For control over the tone character by envelope change a number of principles, as shown in Figure 16, are available. For example: to change the dynamic



character from that of the piano, beginning with percussive transients and falling logarithmically in amplitude, to one without percussive transients and with an initial rising amplitude, like that of wind instruments, we may use the principle of resonance, as illustrated by A. If one string be struck, and if pick-up be confined to a coupled resonant string, this complete change of dynamic character will be provided. For percussion, piano-like, tone, translation may be from the struck string; intermediate effects may be had by combining the two strings' vibrations.

Or, we may strike two similar strings, damp one and pick-up from the two with either mechanically or electrically reversed phase, as shown at B. The initial portions of both neutralize, due to reversed polarities of charge; the undamped string, continuing, as the damped one falls rapidly in amplitude, provide together, the rising amplitude character, devoid of percussion transients peculiar to the wind instruments. Again, other tone-envelope shapes may be secured by translating from the damped string, alone, or from both, with aiding phase.

Another method, illustrated by C, is to use a somewhat flattened string, strike it along the long axis of its cross-section, and apply pick-up normal to this striking direction. Such a string is in a condition of dynamic unbalance when first struck. It starts vibrating in the striking direction and then gradually swings about in a direction at right angles. A pick-up of length greater than the maximum over all vibration amplitude, positioned at right angle to the string's axis, and parallel to the string's initial vibration direction, will not translate during this early part of the tone, containing the percussion noises, but will translate efficiently as the direction of the string's vibration swings around normal to it. Thus the wind instrument starting characteristic is again obtained.

We may, in other methods, shown in Figure 17, so influence the pick-up apparatus by delaying its translation efficiency, that it is insensitive to the percussion transients, and so that its sensitivity builds up

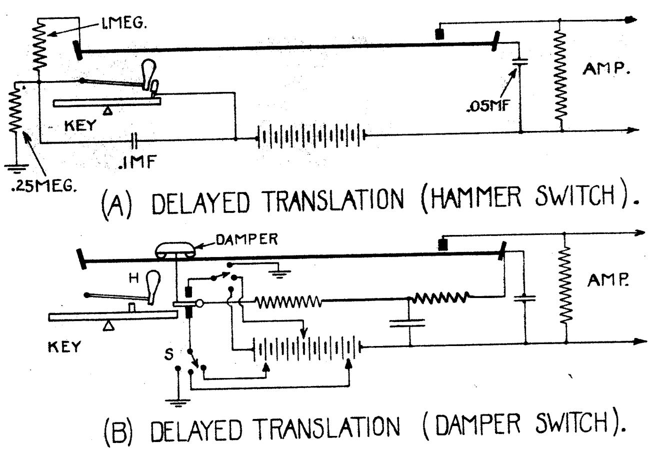


Fig. 17. TONE ENVELOPE CONTROL PRINCIPLES.

and continues in any desired manner. With the electrostatic translation systems this delay may be secured by use of a switch operated by the key, hammer, damper, or other part of the action. If, as in A, the hammer be used, a contact between it and its back-check will close a circuit after the percussion transients have subsided. If that circuit include a condenser in parallel with the string, necessarily now insulated, and a resistance, in series to the switch and charging voltage source, then the delay is secured by delay in the application of the charging voltage on the string and the consequent delay in the building up of the translation efficiency for that string; this delay may be made as slow or fast as desired, by choice of the time constant of the resistor condenser circuit. In order that the operation may be repeated, the string and its associated condenser must be discharged when the key is released. It may be discharged, as in A, by a permanently connected resistance, across which the charging current maintains the charging voltage, so long as applied by the key-controlled switch; or it may be discharged, as in B, by use of a double-throw switch, which connects the string, through its delay circuit, to the charging voltage, when the key is down, and which, when the key is released, discharges the string and condenser, again through the delay circuit. The inclusion of the delay circuit also in the discharge path is not so much for the purpose of delaying the discharge as to prevent reproduced click noises resulting from too sudden a change in string potential. A condenser across the switch contacts prevents these noises when the switch opens. To further prevent too rapid potential changes, at least one of the switch contacts should be of a type providing decrease of resistance with increase of pressure. A small pad of soft leather impregnated with a dilute solution of colloidal graphite very simply provides this requirement.

Until very recently the present instrument had the hammer and back check type of switch in operation throughout. A detail view of this type of delay action is shown in Figure 18. Here the hammers and back checks,

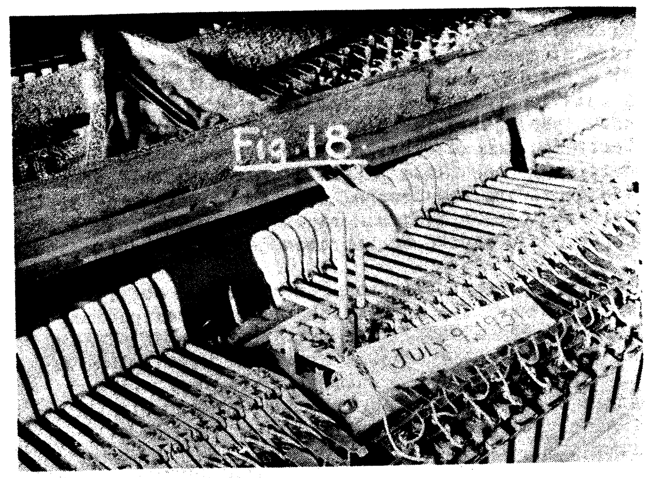


FIG. 18
HAMMER—BACK—CHECK TYPE OF DELAY—ACTION SWITCH.

with aquadagged-leather contact surfaces, connecting wires, and the condenser and resistors of the delay circuits, are shown. This scheme is still in use in the region above that provided with dampers, that is, in the top twenty-one notes. In the rest of the instrument we have recently installed the improved damper type switch. I show this, in detail, in Figure 19. Note the small rods on top of the dampers. These push up the flexible switch poles, which contact in up and down positions, with aquadagged felt pads cemented to brass

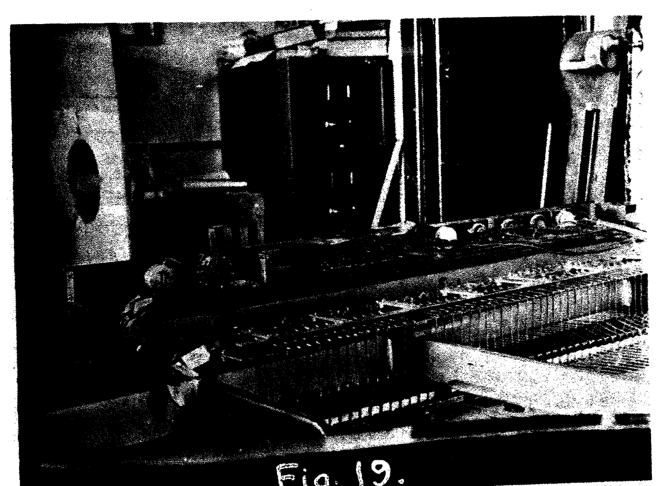


FIG. 19
DAMPER TYPE OF DELAY—ACTION SWITCH.

strips. The spring switch poles connect, through two section filters, to the strings. The brass strips are connected to the main, multipole switch, for control of their connections to the polarizing potential source or ground. Shown here also are the various control and switching connections.

ARTIFICIALLY-INCREASED TONE DAMPING

To reverse the delay action, that is, to permit normal initial translation of the string vibration with its percussion transients, but to artificially increase its rate of decay to any desired degree, the string may be normally fully charged but immediately start discharging as soon as the key is pressed. The rate of decay of translation efficiency may be varied by connecting this discharge circuit to some point on the charging voltage, source lower than normal, such as one third, one half, zero, or even reverse voltage.

There are important musical advantages with this artificial damping control. For example, with some types of music the normal damping of our strings, without a coupled soundboard, may be too low. The effect of this is a muddling or running together of tones in rapid passages. In previous demonstrations of the Electronic this muddling effect has been noticed by some musicians. Now it is possible to adjust this damping, thus providing any desired degree of distinction of individual tones played in rapid succession. The exact degree found in the best pianos can be obtained.

An important additional advantage is obtained with this scheme. The artificial damping control may be made to operate only on the early portion of the tones, and thus leave the remainder to go on with the low damping of the string, thus obtaining the very much desired sustaining power, without increase of muddiness in rapid playing. For special effects, such as harp, banjo, drum, etc., the higher damping rates are used.

The time, translation-efficiency characteristic obtainable with these delay circuits, may be adjusted to different forms as shown in Figure 20. Here (a) shows the zero voltage axis and, above it, the normal, steady-voltage impressed on the strings for full, unmodified, translation of the string vibrations. At (b)

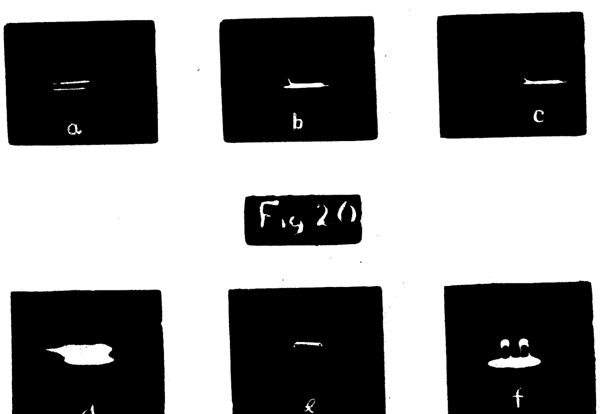


FIG. 20
OSCILLOGRAMS OF STRING-CHARGING VOLTAGE AS CONTROLLED BY DELAY CIRCUITS.

is shown first, normal charging voltage at the left, then the decrease to a moderate degree of artificial damping by decreased translation efficiency. At (c) a quite high artificial damping is provided by a quick drop to a low charging voltage. At (d) is shown the effect of two key blows in fairly rapid succession with a moderate artificial damping adjustment. At (e) is shown the rising characteristic adjustment for wind instrument tones. Here the string voltage is zero until its key is struck. Then the delay action switch connects the string, thru its delay circuit, to the charging voltage source. The smooth rise of the voltage to a steady value in about one fifth second is here shown. At (f) is shown the rise and fall of string voltage, for this wind instrument adjustment, when a note is rapidly repeated by key blow. As soon as the key is released its switch opens the charging circuit and discharges the string and its associated condenser, after which the next key blow repeats the charging action. So long as the key is held, the string voltage remains constant.

In Figure 21, I show some oscillograms of a vibrating piano string (middle C-261.6 cycles) without and with modifications in its envelope shape, introduced by these time-translation-efficiency controls.

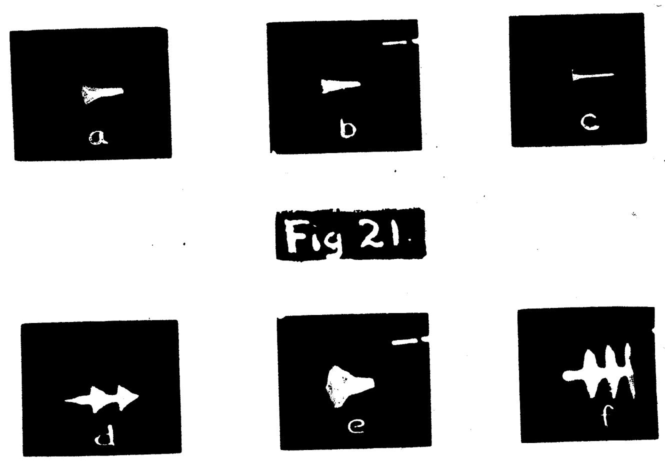


FIG. 21
OSCILLOGRAMS OF TRANSLATED STRING VIBRATIONS AS INFLUENCED BY DELAY CIRCUITS.

The normal, unmodified envelope of this string vibration, as it appears in voltage across the loudspeakers of our electrical translation system, is shown at (a). This does not show the whole tone, because it continued too long for the one-second sweep period of the oscillograph. Notice the abrupt inception and immediate decaying of the vibration at a slow rate. In (b) is shown the same tone with its envelope modified by a slowly-falling time-translation-efficiency characteristic. Observe here the moderate increase in damping of the tone. In (c) a quite rapidly falling characteristic was used, producing a tone of markedly greater damping. In (d) is shown the effect of an artificial damping of moderate degree plus the mechanical damping of the felt string-damper with a rapidly repeated tone.

WIND INSTRUMENT TONES FROM STRUCK STRINGS

In (a) is shown the delayed inception of the tone caused by the rising voltage characteristic adjustment. Comparing this with the unmodified string vibration shown in (a) we see that the abrupt inception of (a) has been changed to a gradual inception in (e), requiring about 1/5th second, thus changing the piano tone into that of a wind instrument.

In (f) is shown a thrice-repeated tone with this same delayed translation efficiency adjustment. The decrease in amplitude at the moment of key release is caused by both decreased translation efficiency and mechanical damper action. In all of these oscillograms showing separate tones the sweep circuit was timed to one second; in those showing repetition action it was adjusted to two seconds.

OSCILLOGRAPHIC APPARATUS

In Figure 22, I show a view of the oscillographic apparatus used in making these oscillograms. A Von Ardenne Cathode Ray oscillograph, o, o, was used with a Dumont Cathode Ray Tube, T, of the time delay type.

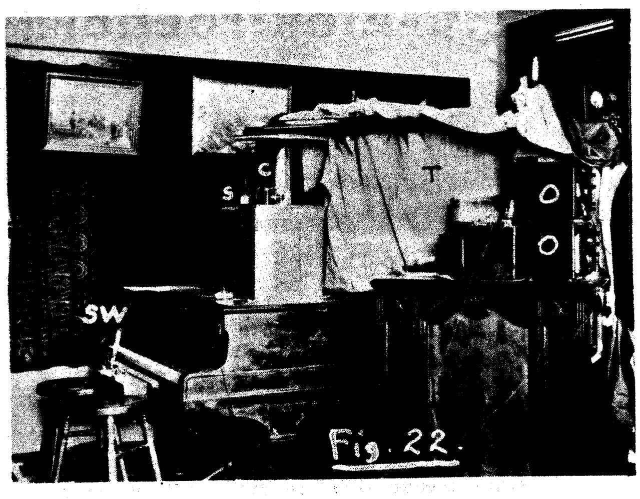


FIG. 22
OSCILLOGRAPHIC APPARATUS SETUP.

A Leica Camera, C, with an electromagnetic shutter-operating arrangement, S, took the pictures. The switch, SW, at left, served to close the shutter-operating magnet circuit, and to start the sweep circuit, when the switch handle struck the piano key. The oscillograph deflecting voltage was taken from a transformer across the speaker voice coils --- for the tone oscillograms last shown in Figure 21; for the voltage graphs of Figure 20 the oscillograph deflecting voltage was obtained from a high-resistance potentiometer between string and ground.

LOCATION OF DELAY CIRCUIT SWITCHES

The most advantageous point in the action, for operation of the delay circuit switch, is in the damper mechanism. With the back-check switch, the organ or wind instrument tones could not be held, after key release, by use of the damper-control sostenuto and sustaining pedals. The reason for this is, that key release opened the string-charging switch, thus discharging the string. Even though the string was allowed to continue in vibration, after key release, by holding the damper up with pedals, this vibration would not translate, due to the lack of translating efficiency caused by string discharge. The organ tone, therefore, could only be held by holding the key down, a technique confusing and limiting to a pianist, who relies very strongly on his sustaining pedal, and, to some degree, on his sostenuto pedal, for sustaining all or given tones after his fingers have quit the keys. These same objections apply equally to a switch located in any other part of the key and hammer action. If however, the switch is operated by some part of the damper mechanism these difficulties are eliminated, for the reason that the dampers are controllable by both keyboard and pedals. When so operated, desired tones, only, may be held by use of the sostenuto pedal, by depressing it after the corresponding keys have been struck, and while they are still held; or any and all tones, once started, may be held by means of the damper, or so called, loud pedal. By such a plan, which we have incorporated in this instrument, the wind instrument or organ tones may be controlled with a normal piano-playing technique respecting both keys and pedals.

ORGAN-PLAYING TECHNIQUE WITH PEDAL

For varying the inception of single tones or chords played slowly, the foot volume control may be used advantageously for introducing, merely by swell pedal control, groups or single tones of wind instruments in an otherwise piano performance. It also aids the hands in building up crescendos or in diminuendo passages.

ENVELOPE-CONTROL MASTER SWITCH

By means of a main, multipolar switch, the individual string-charging switches may be so connected that either percussion or organ type tones are secured throughout the keyboard range; or one half may be made organ, the other percussion, or the reverse of this may be secured. To prevent loud noises in the reproducers, caused by the sudden and large voltage shifts in the pick-up system, resulting from the operation of this master switch, inter-position and overlapping segments on this switch provide, with a contactor, for short circuiting the 500 ohm line to the power amplifier as the switch changes position.

CONTROLS

In Figure 23, I show the various controls in a close-up, front view of the Electronic. At the extreme left is a master volume control for setting the extreme volume obtainable by the foot swell. Next comes the three amplitude and phase reversing controls for the

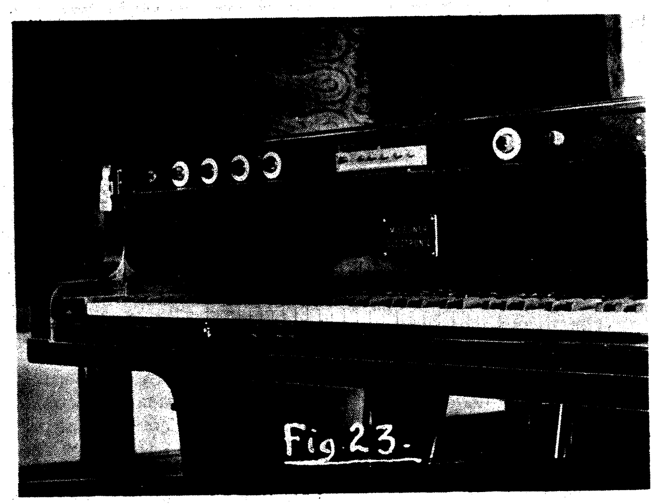


FIG. 23
CLOSE-UP OF ELECTRONIC PIANO CONTROLS.

manual mixing of the three pick-up tube amplifier outputs. Next is the amplifier-frequency characteristic control. In the middle is the preselected tone quality switch group of six buttons. The extreme left button is a red one and, when pushed in, serves to switch in the manual mixing controls to its left, or, when out, the other five buttons at its right, controlling preselected, tone mixtures. If one of these be pushed, with the red button already in operation, the red one springs out, disconnecting the manual controls, and the new one takes effect; or if one of the other preselected qualities be now desired, a push on its button will release the last and give the new quality. Next to the right is the master polarizing voltage control switch. This has four positions. One provides percussion tones throughout the piano keyboard; the next, wind instruments throughout; the next percussion below middle C and wind above; the last wind below middle C and percussion above. With any of the adjustments of this switch all of the tone quality controls are effective. The last knob, at the right, controls the artificial damping of percussion tones. Not shown in this picture are the swell, damper, and sostenuto pedals below on the lyre.

This completes, except for details, the description of what I have come to call my ELECTRONIC PIANO, wherein are brought together a very new and a very old art.

PATENT LITERATURE

For details of its construction, and for much more complete explanation of its operation; for other alternate methods and constructions, and improvements, and for descriptions of some wholly new electronic musical instruments, I refer you to our nineteen already issued patents, appearing as an appendix to my paper; numerous other patents will issue in the future.

COMMERCIAL DEVELOPMENTS

With regard to Commercial developments, these may be worked out in many ways.

No great skill is required in making an electronic piano. With the removal of the acoustic principle of its operation has gone practically all the artisanship of its construction. Furthermore, since the strings are no longer called upon to vibrate a large soundboard, they need not be nearly so long, or so large, or so high in tension. The iron plate on which they are strung may then be made smaller and lighter; the rim, and beams attached to it, no longer called upon to restrain the outward push of the soundboard, caused by the downward pressure of the strings, may now be much lighter; there need be only one or two strings where now there are three.

These changes in the piano itself make it much smaller, much lighter and much cheaper to manufacture. In fact the smallest baby grand provides more than sufficient size, and much more strength and weight than is required for our electronic design.

The electrical apparatus required to make it function is hardly more complicated than a good radio set. As a matter of good judgment, the audio frequency amplifier, reproducers, and power supply can serve, not only for the piano, but very logically, for a radio frequency amplifier and detector, and for a phonograph pick-up also. Such a complete instrument, providing radio, phonograph, and electronic piano performance, could surely be manufactured as cheaply as a good piano of moderate size. For very cheap instruments we may use the entire amplifying and reproducing equipment of an existing radio set, and provide in the piano, only a small tube oscillator, whose input to the radio set would be modulated by the vibration of the piano strings to and from the electrostatic pick-ups. Or, we may use only the audio amplifier and reproducers of the radio set, by providing a small preamplifier in the piano. Another branch of commercial activities might concern itself with conversion of existing acoustic pianos into Electronic pianos.

COMMERCIAL DESIGN

In Figure 24, I show a commercial design of an ELECTRONIC PIANO of this type, made under patent agreements with my own company, Miessner Inventions, Inc., and with Oskar Vierling, of Berlin, by the well known piano manufacturing company, August Förster, at Löbau Saxony, and in Czechoslovakia. These are now on the market in numerous foreign countries, and are known by the name "Electrochord."

SUMMARY OF IMPROVEMENTS

I have previously mentioned that all conceivable or useful controls over tone character such, for example, as feed back, to keep strings vibrating as long as keys are held, are not included in the present instrument. Among those included, in addition to those of a normal piano, are:-

1) A rather full control of harmonic composition, within the limits of the spectrum of the struck string.
2) Control of the tone envelope shape, except for indefinitely sustained tones.
3) Mass dynamic control by foot swell.

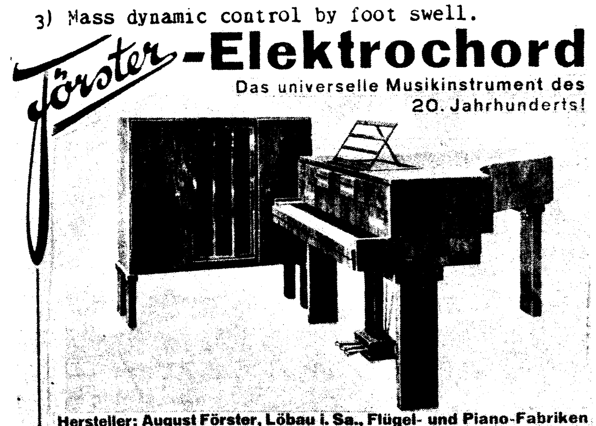


FIG. 24
COMMERCIAL DESIGN OF ELECTRONIC PIANO MADE IN GERMANY.

In addition, the divided keyboard permits, when desired, simultaneous play, in different registers, of tones differing in character by change of envelope shape.

CONCLUSION

In conclusion, and before beginning our demonstrations, I wish to express my thanks to the Radio Club of America, and to Columbia University and Doctor Dykema, for their kindness in arranging this meeting, and to my audience for its attentiveness to a long, and arduous technical paper.

I wish, further, to thank my brother, Dr. W. Otto Miessner, of Chicago, for his original suggestion some ten years ago of the piano as a research problem, and for his musical guidance from time to time; to Mr. Anton Rovinsky, for his many helpful suggestions; to Mr. Harold Bauer, for his interest and criticisms; to Dr. Erwin Meyer, of the Heinrich Hertz Institute, of Berlin, for use of his Spectral analyses of Musical instrument tones, shown in Figures 1, 2, 3 and 4; to Dr. Dayton C. Miller for oscillograms of violin and voice tones in Figures 4 and 5, from his "Science of Musical Sounds"; to my collaborator, Dr. Oskar Vierling, of the Heinrich Hertz Institute, of Berlin, with whom I have a cross-licensing patent agreement; and finally to Mr. Charles T. Jacobs, my technical collaborator and patent attorney, who has made numerous important technical contributions to this work during the past three years.

APPENDIX

LIST OF ISSUED PATENTS IN U. S. A.

SUBJECT	Number	Issue Date
Photo Electric Organ	1,886,687	Nov. 8, 1933
Multiple Pick-up Tone Control	1,906,607	May 2, 1933
Bucking String Organ	1,912,293	May 30, 1933
Sidewise Translation	1,915,858	June 27, 1933
Time Delay Organ	1,915,859	June 27, 1933
Translation-efficiency Variation	1,915,860	June 27, 1933
Multiple Translation	1,915,861	June 27, 1933
Tone Control By Sidewise Pick-up	1,929,027	Oct. 3, 1933
Amplifier Frequency Control	1,929,028	Oct. 3, 1933
Inter-vibrator Coupling	1,929,029	Oct. 3, 1933
Uncouplable Soundboard	1,929,030	Oct. 3, 1933
Sustained Tones by Feedback	1,929,031	Oct. 3, 1933
Tone Control Stop System	1,929,032	Oct. 3, 1933
Different Vibrators for Tone Types	1,933,294	Oct. 31, 1933
Resonant String Organ	1,933,295	Oct. 31, 1933
Non-linear Translation	1,933,296	Oct. 31, 1933
Longitudinally-vibrated Bars	1,933,297	Oct. 31, 1933
Flattened String Organ	1,933,298	Oct. 31, 1933
Timbre Control, Formants, etc.	1,933,299	Oct. 31, 1933