Design of Electronic Organs

WINSTON WELLS* **PART I**

In this series of articles, the author presents a thorough discussion of the design and operation of electronic organs.

"Jesus Maria! I play it so good an' it comes out lika this!"

THUS SPOKE FERDINANDO GERMANI, the celebrated Italian concert organist, upon playing an electronic organ for the first time. This was about a decade ago and, at the time, Germani had just signed a contract to play a series of demonstration recitals for the manufacturer of the instrument.

The maestro was not alone in his dismay, for the performance of the little instrument was a decided letdown to those who were accustomed to the pipe organ at its best. True, it surpassed the finest of pipe organs in dynamic range and rapidity of action. It was compact and readily portable, and its cost was but a small fraction of its nearest non-electronic competitor. But it was lacking in tonal resources, some of the controls were awkward to manipulate quickly and there were other points of design which violated the most sacred traditions of organists and organ builders.

Now it is not to be supposed that, even in this day of wonders, a device so complex as an electronic organ should spring, fully grown and perfect, from the head of its creator, in the fashion of Minerva. Rather, any art must go through a long period of evolution, building a background of trial and error, before approaching the goal set by its pioneers. But an intelligent consideration of the fundamentals upon which the art is based, and an awareness of the objective, can do much to bring the goal closer.

It is the purpose of this article to acquaint the reader with the requirements of good organ design, to discuss the mechanical and electrical structure of modern commercial instruments, and to point out the trend of design in future types.

Design Fundamentals

When we, as engineers, are asked to design a given device, three questions come into our minds:

(1) What is it supposed to do?
(2) How many are to be made at a time?
(3) At what price does it have to sell in order to yield a profit which justifies the undertaking?

Upon the answers to these questions is based the work of the entire project which follows, from the first crude sketches and rule-of-thumb computations to the finished product. The physical structure of the device is then evolved with the objective of satisfying the requirements of performance, production and cost.

Perfection is not ordinarily sought in industrial practice but instead, every effort is made to establish a practical compromise between ideal performance and low production cost. It is the judgment exercised in balancing these two factors which largely determines the ultimate utility of the product.

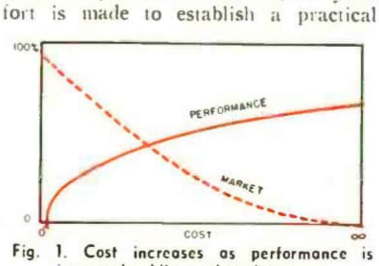

Fig. 1. Cost increases as performance is improved, while market decreases.

It is apparent that the potential sales of a product will increase as the price is lowered, or as the performance is improved. An increase in rate of sales will permit the use of more efficient production methods which, in turn, will lower the cost of manufacture and, consequently, the cost to the consumer. However, it is difficult to make substantial improvements in a product without raising the cost of production.

By means of data obtained through engineering estimates and market surveys, it is possible to plot reasonably accurate graphs for any product, showing the relation between market, performance and cost. The point at which the performance and market curves intersect determines the optimum consumer price and, also, the standard of merit to which the product must be designed. *Fig. 1* shows the manner in which these graphs are applied to a hypothetical product.

Before attempting an analysis and criticism of the current instruments, and before discussing means for improving them, it is necessary that we consider the position the electronic organ occupies in the field of music. While it is inherently capable of some things which are impossible to the pipe organ, its prime function is that of succeeding the pipe organ in the musical world.

The modern pipe organ is the end product of several centuries' development work, and it represents the combined efforts of many men who were outstanding in the fields of music, acoustics and mechanics. The instrument is one of the most functional devices ever to be built by man, its design being shaped by the combination of musical requirements, human anatomy and the mechanical limitations under which the organ builders worked.

The introduction of electronics to the production of musical tones has conquered many of the limitations imposed by the use of pipes and reeds, but it has changed neither the mind nor the anatomy of the human being, nor, in consequence, the organist and his audience. Therefore, we may well examine the pipe organ, and ascertain the reason for its design, before planning an instrument which we arbitrarily call "an electronic organ".

In its modern form, the pipe organ is essentially a sustained tone, multi-keyboard instrument, capable of rendering polyphonic music, and capable of covering the entire frequency range useful in music.

Acoustical Oscillators

The musical tones are produced by organ pipes, which might be described as "acoustical oscillators", the simplest of them resembling the tin and wooden whistles sold in toy shops. The pipes are driven by a regulated air supply, the pressure of which is usually between five and twenty inches, measured on a water manometer. In some cases the pressure may be as high as thirty inches, and a few pipes have been built to operate at one hundred inches.

A separate pipe is used for each note, and for each separate tone color. A set of pipes, all of the same tone color but graded chromatically in pitch, is referred to as a "rank" of pipes, or as a "stop".

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Each rank of pipes is mounted on a wind chest, which is supplied with air from the regulator. The receptacle which holds the base of each pipe contains an electro-pneumatic puff valve which, through a series of switches and relays, may be connected to the proper key on one of the organ's manuals or the pedalboard (hand or foot keyboards, respectively).

The common return circuit for the notes of one stop is brought through a switch, located on the console in a position convenient to the organist. The handle of this switch is called a "stop tab", "drawer knob" or "rocker tab", according to the particular form which it takes. Thus, when a stop is "on", the pipes in the rank will speak (play) when their corresponding keys or pedals are depressed. Conversely, when a stop is "off", the pipes of that rank are silent, even though the keys may be depressed.

Very small organs may have only three or four ranks of pipes; the largest may have several hundred. The pipes, along with the more bulky apparatus in the instrument, are housed in an "organ loft", which is located with a view toward obtaining good sound distribution over the area to be covered. The console may be remotely located, provided the organist can hear the sound from the loft above the reverberation and room noise. At very great distances, of course, the time delay effect becomes objectionable . . . the organist may have played several successive notes before he hears the first one!

The Console

The console is the control center of the instrument, and is designed to permit playing and changing of tonal effects with a minimum of bodily movement on the part of the organist. Since the bass passages are played with the feet, the legs, as well as the arms of the organist, are in constant motion, leaving the buttocks as the only means of bodily support. This fact is of considerable importance when deciding upon the location of controls, for they must be so placed that the body will not be thrown off balance while manipulating them.

The pedal board, upon which the bass is played, is so located that its keys are accessible to the organist's feet, as he swings his lower leg from side to side, the keys being arranged in a radial pattern to conform to the arc traced by the foot. There are thirty-two pedals, covering the range of two octaves and a fifth, chromatically, the lower (left hand) end starting with C, and the upper (right hand) end terminating with G. The pedal contacts are usually designed to "make" when the pedal has been depressed about one inch. The pedals which correspond to the "black keys" on a piano, are raised a couple of inches above the others.

The manuals (hand keyboards) are located in front of the organist, and are arranged, one above the other, in "staircase" fashion. The lower one is approximately at elbow height and each successive one is raised by another 2½ inches. The upper ones slope toward the organist, to compensate for the change in attitude of the wrist when playing them.

There are sixty-one keys on each manual, covering a range of five octaves chromatically, starting and ending on C. The exposed portion of a "white key" is 4¼ inches long. They are identical to piano keys, except that the ends facing the organist are undercut. The upper and lower manuals overlap slightly, and this undercut permits the playing of one hand directly below the other, on separate manuals and with minimum interference of motion. The electrical contacts "make" when a key is depressed about one-half inch. The key action is designed to respond to a finger pressure of from 1½ to 4 ounces.

Above the manuals, and to the sides, the stop tabs and other controls are arranged in rows, and are grouped according to their functions. In some consoles, they are mounted upon a semicircular or elliptical panel, so that they may all be reached by one continuous sweep of the organist's arm. (This has proven to be an excellent design, and it might well be used by builders of electronic instruments.)

Modern organ playing necessitates the very rapid changing of registration. ("Registration" is the term applied to the particular tonal effect which is momentarily set up upon the manuals and pedals.) Since a change in registration may easily involve the simultaneous movement of fifty or more stop tabs, it becomes necessary to perform this function mechanically.

The larger pipe organs are equipped with rows of push buttons, called "combination pistons", these being mounted upon narrow panels, under their respective manuals. When a piston is depressed, (usually by means of the knuckles) an electro-pneumatic mechanism is set in motion, which moves the stop tabs according to a pre-arranged registration. These registrations are set up upon a "recorder board" in the rear of the console. There are usually provisions for setting about thirty registrations at one time, although extremes may vary from ten to several hundred.

Upon having depressed and released a piston, the organist may quickly modify the registration thus obtained, by changing a few stops by hand.

Joan Curtis at the Hammond organ.

The organ is not a "touch responsive" instrument. That is to say that, for a given registration, a note will sound exactly the same, regardless of the manner in which the key is struck. Therefore, expression must be obtained by other means. It is standard practice in modern pipe organ design to cover the opening to the organ loft with a set of movable soundproof shutters. These, when closed, attenuate the escaping sound about 30 db in the better instruments.

Expression Control

The "swell shutters", as they are called, are coupled through an electro-pneumatic servo-mechanism to the "swell pedal" (sometimes called "swell shoe" or "expression pedal"). This pedal responds to a forward or backward rocking motion of the foot, the shutters being open when the foot is in the toe forward position. The swell pedal is located so as to be operable by the right foot, since the greater number of the bass notes are played by the left foot.

The pipes of the larger instruments are often divided into several groups, each group being housed in a separate organ loft. In such cases, it is customary to connect the shutters of the separate lofts to individual swell pedals, thus permitting the "fading" of one musical passage with relation to another. By means of a switch, they may also be ganged together electrically.

The utility of the swell mechanism in pipe organs has been somewhat limited, both by the mechanical inertia of the enormous shutters required, and by the difficulty of maintaining a good ratio of sound attenuation between the open and closed positions. From this standpoint, the electronic organ is infinitely superior, since an ordinary bass compensated volume control, connected to a swell pedal, gives all that one could ever wish for in a swell action.

Originally, the swell pedal was limited to the effecting of gentle, gradual changes in loudness of musical passages but, in modern instruments, it is used to obtain marked diminuendos and crescendos, as well as for accenting individual notes in a passage.

The "crescendo pedal" is located to the right of the swell pedal, and is identical in construction. It actuates a progressive multi-contact switch, the contacts of which are connected into the stop actions. As the pedal is "opened", an increasing number of stops are made active until, at the full open position, the organist is using "full organ" (all of the instrument's stops in use). This device is extremely useful in building musical climax, especially on large organs, where there is a fairly even graduation of loudness between successive stops.

Stops

Upon examining a pipe-organ console, it will be noted that the stop tabs are labeled with the name of the instrument or effect which the stop is supposed to represent. This name is followed by a numerical notation, the most common ones being: 16′ 8′, 4′, 2 2/3′ and 2′. These notations refer to the musical "register" pitch of the stop, and are derived in the following manner:

The lowest note on an organ manual is the second octave below middle C (65.41 cps). An open pipe, approximately eight feet long, will produce this note when blown. Hence, any stop whose second octave below middle C coincides with the lowest key on the manual, is termed an eight foot stop.

A stop whose lowest note is three octaves below middle C will need a pipe sixteen feet long, to produce this lowest note. Thus, if this lowest note coincides with the low C on the manual, we are said to have a sixteen foot stop. It will be noted, in this case, that if the the middle C key is depressed, we actually play the octave below middle C. We can best remember this system of notation by keeping the following in mind. When we set up a registration of 8′ stops, the notes which we play on the keys are sounded. When we use 16′ stops, the organ sounds at an octave below the notes which we are playing upon the keys. With 4′ stops, the organ sounds at an octave higher than the notes being played. A 2′ stop will sound two octaves high, a 32′ stop, two octaves low, and a 2 2/3′ stop will sound the twelfth interval (an octave and a fifth) above its nominal position on keyboard.

The same system is used in the notations on pedal stops. However, the lowest note on the pedal board is, nominally, three octaves below middle C, so it is the sixteen, rather than the eight-foot stop, which sounds the note corresponding to the pedal being depressed.

Stops of one register may be played alone, or in combination with those of another. The foundation of organ music depends upon the eight-foot stops on the manuals, with the sixteen-foot stops on the pedals. Those of the lower registers add "body" to a passage, while those of the upper register lend "brilliance."

Couplers

In addition to the stops of various registers, most organs are equipped with "couplers", to which the same form of notation is applied. The control tabs are identical to those used for the stops. When a 16′ coupler is added to a manual, the organ will duplicate, at an octave lower, everything set up in the registration of that manual. Likewise, a 4′ coupler will duplicate the registration at an octave higher. Another control, which is labled "unison off", will silence the original registration, but will allow it to "speak" in the register of any couplers which may be on.

There are also four, eight and sixteen foot inter-manual and manual-to-pedal couplers which, as their names imply, can duplicate the registration of one manual upon another, or upon the pedals. Couplers, when properly used, are of tremendous value in extending the usefulness of a stop, and in making the organ a more flexible instrument.

Another important part of the pipe organ is the "vibrato", sometimes called a "tremolo" or "tremulant". The same terms are also applied to the effect produced by this device.

Vibrato

Vibrato may be defined as a rapid cyclic variation in the pitch of a note, the rate of variation ranging from about 4.5 cps to 12 cps in extreme cases, and the pitch variation ranging from plus to minus 0.5% to 5% of the nominal frequency of the note. We may also define vibrato as the frequency modulation of a musical tone.

As applied to music in general, the frequency and amplitude of vibrato vary among individual performers, and are different for different types of instruments. In the human voice, the rate averages about 6.5 complete beats per second, with a pitch variation of plus to minus 1.3% of the nominal frequency. The violin vibrato averages a little over 7 cps with a pitch variation of about plus to minus 2% of nominal frequency.

While the dominant characteristic of the vibrato is one of frequency modulation, amplitude modulation also occurs in most cases, as well as a whole series of complex phenomena arising from "side band" effects. Since there is always some reverberation in a room, we hear all of the successive pitch variations of the tone and its partials (harmonics included) simultaneously. These beat with each other and their resultants, in turn, beat with them, and so on, ad infinitum.

Vibrato is of profound significance in all sustained tone music, since its introduction into a tone has a direct effect upon the emotions of the listener, regardless of the character of the music being played. The subject should be thoroughly studied by anyone concerned with sustained tone instruments, whether as a performer, composer or designer.

The vibrato is seldom employed in percussive tones, since it softens the attack and gives an effect which is generally displeasing to the ear. An exception is the case of the vibra-harp. This instrument resembles the xylophone, both in structure and in manner of playing. It has a series of tuned cylindrical resonators hung below the resonant bars to bring out the fundamental tone. The necks of these resonators are fitted with motor driven rotating dampers which impart a kind of "amplitude vibrato" to the tone of the instrument, the effect being quite pleasing.

The statements made regarding the vibrato in vocal and instrumental music are generally applicable to the organ. Large pipe organs have several vibratos, these being effective on individual stops or groups of stops. It is highly desirable to be able to apply vibrato selectively to various stops, without affecting the rest of the instrument. The smaller organs usually have but one vibrato, this being effective upon the entire instrument.

Vibrato is effected in the pipe organ by means of a device which pressure-modulates the air in the wind chest at the desired rate, causing the tones of the pipes to rise and fall in pitch. The "on and off" control is brought out to a conventional stop tab at the console.

Varieties of Tone

The reader may have wondered, by this time, why the pipe organ has so many stops, especially since it has been pointed out that a single one may be built to cover the entire compass of pitch necessary to the instrument.

The primary reason is that any one tone color, no matter how beautiful it may be, will become monotonous when heard for more than a few minutes at the most. This goes back to a fundamental law of biology and psychology, which states that an organism loses its power to respond to a given stimulus when that stimulus is applied over too long a period. A one-hour performance by a chorus of angels would become as irritating as a convention of Swiss bell ringers, providing they did nothing to vary the act.

The second reason is that various types of music, and musical passages, require widely different tonal treatment. One would scarcely expect to hear a piece of sacred music played with the "wah wah" trumpet effect which is featured in jazz bands, nor would he relish hearing his favorite popular tune rendered with the somber dignity of an anthem. Music, being an abstract expression of human experience, must be capable of registering that experience in a form appropriate to our understanding.

The third reason is one of tonal balance. It is often desirable to have a given stop available in several degrees of loudness. Since there is no practical method for making the volume of sound from a pipe instantaneously variable, the only solution lies in providing several similar stops, graded as to intensity.

The fourth reason has to do with the "ensemble effect" or "grande celeste", as it is sometimes called. The pipes of an organ, like the instruments of an orchestra, are never perfectly in tune, although the deviations in tuning may be too slight to be directly apparent to the ear. However, when many notes, each differing slightly in pitch, are played in unison, a particularly pleasing effect is produced.

This pleasing quality of the grande celeste seems, in part, due to the complex beats which arise between the various notes and their partials. There is also the fact that the ear dislikes a tone whose pitch is too sharply defined, as much as the eye dislikes a line whose edges are too sharply drawn.

While the grande celeste is undesirable in certain types of musical passages, it is absolutely necessary to the building of musical climaxes, and it can only be obtained through the use of many ranks of pipes, played in unison.

Organs designed in strictest tradition have their stops divided into carefully chosen groups, each group being assigned solely to a given manual (or the pedals). The stops assigned to one manual are not available on another, except through the use of couplers. When a single rank of pipes is so connected that it is available as an individual stop on two or more manuals (or manual and pedal), it is said to be "duplexed". When a single rank of pipes is provided with individual octave couplers, so that it may be used independently as a 16′, 8′ and 4′ stop on one manual, it is said to be "unified". It is, of course, possible that a stop be duplexed and unified at the same time.

Unification and duplexing can extend the resources of an organ enormously, especially a small organ. There are two serious disadvantages, however, to their unrestrained use. The first of these comes in attempting to play the same note on two different manuals simultaneously. Obviously, if the same pipe is being used for both, the note will sound

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George Wright and Miss Gaumer of the Hammond Organ Co. with Solovox attachment for organ.

—NBC Photo

Electronic Organs

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no different with two keys depressed than with one. The same criticism applies when attempting to play in octaves on one manual, using, say, eight and four-foot stops taken from the same rank of pipes.

The second disadvantage lies in the fact that a rank of pipes must be very carefully balanced in loudness over its entire range. This process is known as "voicing". A stop, at its best, is voiced differently for different uses and, particularly, for different registers. Therefore, when a stop is to be used for many purposes, its voicing must be a compromise of all of them.

We may conclude this portion of the article by stating that the pipe organ has attained a fairly high degree of perfection as a musical instrument. Its chief musical limitation is in the mechanical inertia of its action, which is an impediment to nuance, and to the execution of rapid musical passages.

Chief among its other disadvantages are its great expense, bulk and weight, the frequency with which it must be tuned and repaired (and the difficulties in doing both), and the amount of power which it consumes (50 kw is not uncommon for large organs).

[*To be continued*]