Anatomy of a Pipe Organ:
An Introductory Module

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December 6, 2005
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MPSY 5340: Musical Acoustics
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ABSTRACT

This brief overview of fundamental acoustical principles of a pipe organ is presented as a teaching module for the inquiring young student in the music education classroom.

This material is intended to supplement an interactive, visual tour and demonstration of a functioning pipe organ. It is designed to illustrate basic acoustical principles that influence the construction and response of various components of the instrument.

The instrument featured in this discussion is the 132-rank Memorial Organ located at Tyler Street United Methodist Church in the historic Oak Cliff district of Dallas, Texas.

The main four-manual console (Casavant, 1940) was acquired from Northwestern University in Evanston, Illinois and dedicated for use in its current location in 1980. It controls both the chancel and rear galleries of the instrument, totaling over 7150 pipes.

The secondary three-manual console (Moeller, 1966) replaced a smaller instrument following a devastating sanctuary fire that destroyed much of the original instrument. It is located in the balcony and controls 31 ranks of pipes in the rear gallery.

INTRODUCTION

The historic pipe organ stands alone among human endeavors as the most magnificent testament of aesthetic majesty, mechanical ingenuity and acoustical intrigue. Many listeners appreciate the aural beauty—and perhaps the technical skill of a gifted performer—without a basic understanding of many mechanical and acoustical principles that enable such an instrument to achieve its artistic splendor. The illustrated discussion that follows will introduce each of four major components of the system: (1) the wind system and bellows, (2) the resonance chambers, (3) the keyboard console and pneumatic action, and (4) the actual speaking rows of pipes. Following this overview, a brief discourse regarding registration will be addressed in more detail.

OVERVIEW OF MAJOR SYSTEM COMPONENTS

The Wind System and Bellows

At its simplest form, the organ produces sound by exciting columns of air that are directed into chambers of resonating pipes which reinforce the specific frequencies and timbres desired by the performer. The lifeblood, then, of the instrument is air, or wind, and the actuator of the modern organ is the wind system or blower motor. Figure 1 depicts one of two blower motors that supply air at a consistent pressure and sufficient volume (that is, quantity) to the bellows of this instrument. In previous generations, the bellows were operated by hand or foot, often by a young apprentice of the organ master.

The accordion-like horizontal bellows in Figure 2 are positioned directly atop the blower. They are regulated by the spring action visible in the foreground of the photo. Air is forced into the resonance chambers via the cylindrical supply pipe at the right. It should be noted that, on occasion, a generalized deficiency of tone is symptomatic of a faulty level of pressure supplied to or from the bellows as a result, for example, of an air leak in the supply pipe. The production of standing waves with appropriate pressure nodes and antinodes within a pipe is essential to the proper functioning of the organ.

The Resonance Chambers

The chambers in which the speaking pipes and encased are equivalent to the arena in which a sporting event is contested. All of the sound-producing components of the organ and its supportive manual and electronic systems are housed in these rooms of varying size and construction. It is in these spaces that complex combinations of speaking pipes first interact (constructive and destructive interference) before transmitting sound into the larger acoustical venue. The photo in Figure 3 is taken from a resonance chamber in the Gallery II. The supply pipe viewed in an earlier photo conveys air to the leather reservoir in the background of the photo. This reservoir is located directly underneath the rank of metal pipes shown in Figure 4. Only a small percentage of this particular resonance chamber, which contains dozens of ranks and many hundreds of pipes, is visible in this photo.

The architectural layout of the various resonance chambers is based on both aesthetic principles and practical, physical constraints of the performance space. The organ in this discussion, for example, was designed in its voicing to offer a full-bodied, symphonic sonority. The pre-existing facility required that resonance chambers and pipes be distributed across a broad horizontal axis and, in the main chancel instrument, throughout two stories of construction space, at times enhancing the original aesthetic objective and at other times conflicting with this aim.

One remarkable type of resonance chamber is typified by the presence of expression shades that can be controlled by a pivoting foot pedal of the performer. These wooden shades can be incrementally opened and closed to impact the dynamic level and timbre of the end-result sound experienced by the listener. While the function of the pipes themselves is unaffected, the acoustical principles of reflection and diffraction produce softer, mellower sound from the division of pipes when speaking behind closed shades. A portion of the swell division of the organ is visible through the half-open shades in Figure 5. Musicians refer to a division of pipes that can be impacted by the use of shades as being "under expression." Since the action of the organ has only an on-off switch capability for each note, unlike the piano which allows various gradations of sound based on the speed and intensity of the attack, the expression shades provide the only opportunity (other than adding or subtracting stops, or voices) for a gradual *crescendo* or *diminuendo* of dynamic strength.

It should be noted that some ranks of pipes are not, in fact, housed in resonance chambers but, rather, speak directly into the hall itself. The unusually shaped reeds of the choir division in Figure 6 and the brilliant, horizontal fanfare trumpets of the rear gallery in Figure 7 are two such examples. The brash, complex waveforms produced by these ranks of pipes require an unrestricted, directional path of sound to the ear of the listener.

The Keyboard Console and Pneumatic Action

In contrast to most symphonic instruments, the organist does not come in contact with the resonating system itself but, rather, controls the instrument from the keyboard console. The main console of the sample instrument, shown in Figure 8, contains four manuals, or keyboards, and a pedal board played by the feet. Each manual primarily controls a division of pipes that are architecturally grouped together in one or more resonance chambers. These manuals can be linked together through the use of the combination action, or couplers, which pair selected divisions to be controlled together by the use of a single manual. (See Figure 9.) A discussion of the application of various divisions of the organ will be reserved for a future discourse.

In sticker-backfall-tracker instruments, such as the Dallas area masterpieces at the Morton Meyerson Center and at Southern Methodist University’s Caruth Auditorium, the keyboard is connected to a set of mechanical dowel levers (“trackers”) that control the horizontal open-and-close action of pallets which release air from the wind reservoir into single, specific pipes. In recent generations, the invention of electro-pneumatic actions, such as is used in the organ in this discussion and in the chapel at the Perkins School of Theology, allows flexibility of the position of the console in relation to the speaking pipes. Figure 10 shows a small sample of the electronic contacts that control the pallets in an electro-pneumatic instrument. The console communicates with these contacts via a massive umbilical cord of electrical wiring.

It is necessary to mention two unique acoustical properties of the organ in relation to the console. First, it is important to note that the speed of sound is finite and the geographical distance between various divisions of the organ, as well as between these divisions and the console, may be significantly great. As a result, in much the same way as musicians in large symphonic forces or antiphonal choirs, various sonorities may reach the performers (and potentially the audience, in poor acoustic settings) at disparate times. This can be demonstrated by the disconcerting experience of standing underneath the fanfare trumpets in the rear gallery while these are sounded in unison with the choir and swell divisions, some hundred feet away. While this phenomenon is independent of pitch and dynamic strength (c.f. Hooke's Law regarding direct proportionality of displacement to restoring force), it does create challenges as a result of the physical distance itself. As a result, organ builders must be cognizant of this phenomenon and its application to the physical layout of the various divisions. Furthermore, performers of expansive instruments in substantially sized halls must be attentive to play "by feel" (or by sight, when performing with a conductor and concerted forces) rather than by a reliance on the untrustworthy aural experience of reflected sound.

Second, it has already been mentioned that the on-off switching capability of the console keys restrict graduated dynamic expression. This similarly relates to the time envelope of decay of sound that is produced. Unlike the piano, the organ produces a sustained tone of static intensity throughout the duration of time a specific key is depressed by the player. As a result, there is no natural "decay" of sound until the key is released and the tone disperses into the acoustical venue itself. This provides both a huge asset for the performer who desires to accumulate sound with the entire resources of an instrument and a cautionary risk for the inexperienced player that may obscure more sensitive timbres with too vast a sound.

The Speaking Rows of Pipes

Each set, row or rank of pipes—these terms are interchangeable—contains the pitches necessary to produce a complete chromatic scale within a specific range. For a typical modern instrument, this is 61 pitches, or five octaves, in most primary rows of pipes. Each set of pipes is activated or deactivated by the use of draw stops, shown in Figure 11. These may be further combined into preset registrations of stops and stored in the "memory" of the instrument by the use of general presets, shown in Figure 12.

The fundamental building block of registration on the primary manuals is the eight-foot (8') principal stop. The pitches produced by these stops correspond with the sounding pitch on the piano if reading from an identical score of music. It should be noted that some pipes function as "open" pipes in the acoustical sense and others function as "closed" or "stopped" pipes. For example, the open diapason G_4 shown central in Figure 13 is approximately sixteen inches in length from where the edge tone is produced to the end of the cylinder. By comparison, the wooden stopped diapason G_4 in Figure 14 is approximately eight inches in length, but produces the identical frequency. Note the "hat" or stopper at the top of this row of pipes. This application is a practical extension of the lab experience that demonstrates the halving of standing wave frequencies in an open-closed pipe versus and open-open pipe. A reasonable hypothesis would indicate that the stopped pipe, which encourages only the odd-numbered overtones in the series, would exemplify a "sweeter" tone. Experience in this specific circumstance bears out this conclusion. Stopped pipes, then, provide an advantage, both by adding a new timbre color to the palate of sound and by reducing necessary space in the resonance chamber for a rank of pipes within a particular set of octaves.

Regarding the length of pipes, one can observe that the lowest note available on the open diapason discussed above, C_2 as depicted in Figure 15, represents the fundamental tone, possessing a pipe approximately eight feet in length. By extension, one would calculate that C_3 and C_4 are, respectively, approximately four feet and two feet in length. One would expect that the C_4 (262 Hz), based on the inverse relationship of frequency and wavelength, would be approximately one-and-one-half times as long as the G_4 (392 Hz), confirmed above to be approximately sixteen inches. This is, in fact, the case and confirms the theoretical principle. It should be noted that these measurements do not precisely match the "ideal" model, due to acoustical idiosyncrasies affected by the proportional diameter adjustments throughout a rank of pipes and the respective shape of the pipe (cylindrical versus conical). A discussion of the various types of pipes—flue pipes, reeds, hybrids and strings—and their various properties will be reserved for a future discourse.

REGISTRATION

Eight-foot principal tones do not exist in isolation. First, in the pedal division, the sixteen-foot designation provides the fundamental building block of tone. Undergirding the sixteen-foot stops, some larger instruments boast 32' and even 64' stops, sometimes produced by artificial means, such as the acoustical resultant tone occurring from the simultaneous sounding of a tonic pitch and the perfect fifth above. The faux echo bourdon shown in Figure 16 may be located in the balcony, far removed from the remainder of the instrument. This is because the huge waveforms of these low frequencies, in contrast to the piercing piccolo stop in the solo division (Figure 17), diffract in an enormous arc, creating a somewhat non-specific, non-directional effect for the listener.

Second, it is important to remember that each pipe produces a complex tone, reinforcing a fundamental frequency and some combination of overtones above the fundamental, as determined by the shape of the pipe, cut of the mouth, and so forth. This can be demonstrated by “overblowing” any pipe by mouth, as on the trumpet, to achieve a higher overtone in the series. This audible member of the series was present in the original, complex tone, but is reinforced by the process of overblowing.

A further method of reinforcing these higher overtones is by the use of subordinate stops, such as four-foot and two-foot stops. When a four-foot stop is used in juxtaposition with its principal counterpart, a single key depressed by the player will produce two tones an octave apart, along with the resultant overtone series of each. The name designations of “four-foot” and “two-foot” are a product of an earlier discussion regarding the length of pipes in relation to frequency. Figure 18 displays a portion of a sample registration chart for the specific organ discussed here. Note, for example, in the Great division, the presence of a sixteen-foot bourdon, eight-foot diapasons and Gemshorn, a four-foot principal and flute, and two-foot recorder and “fifteenth” (named after the interval of two octaves).

Two other special types of stops should be mentioned in this discussion of registration. Mutation stops, or off-unison ranks, function differently in character from other stops of the principal variety. When C_2 is depressed, for example, on the Quint 5-1/3 mutation stop in the pedal division, C_2 does not sound as the fundamental tone. Rather, G_2, a perfect fifth higher, sounds as the principal tone, building a new harmonic series on the dominant. The designation “5-1/3” acknowledges that the proportion of eight feet (the principal fundamental length) to 5-1/3 feet produces a pitch of 1.5 times higher frequency in Hertz, thus a perfect fifth. Similarly, the Tyler Street organ choir division includes a “duodecima 2-2/3” (representing an octave-and-a-fifth), a “decimasepta 1-3/5” (two octaves-and-a-third), and a “decimanona 1-1/3” (two octaves-and-a-fifth).

When various mutations are packaged together, a mixture, a type of specialty stop, is formed. Mixtures, given titles such as Sharp Mixture IV, combine numerous ranks of pipes indicated by Roman numerals, to produce a complex, colorful tone for a unique aural effect. Basic acoustical principles suggest that the presence of a solid fundamental in these situations assists the listener in appreciating the complexity and beauty of these chorus-like stops. Skill in registration blends art and science and requires both technical expertise and aesthetic taste.

CONCLUSION

Much remains to be written in order to dissect and analyze the inner workings of this substantial instrument. Topic for future study include discussion on the following: (1) the methodology of voicing an instrument, the process by which each individual pipe is painstakingly notched and shaped to ensure a consistent, pleasant timbre throughout the instrument; (2) the customized construction and layout of chests of speaking pipes within the instrument to match a particular acoustical venue; (3) the tedious process of physically tuning an instrument that contains thousands of pipes of various temperature- and humidity-sensitive materials, spanned over a significant area of space and distance;

and (4) the artistic endeavor of registration, by which the talented performer selects complex configurations of stops to realize, or orchestrate, a specific musical composition. An instrument whose concept extends two millennia into the historic past deserves the commitment of many future generations to continued study, appreciation, and enjoyment.

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Figure 1

Figure 2

Figure 3

Figure 4

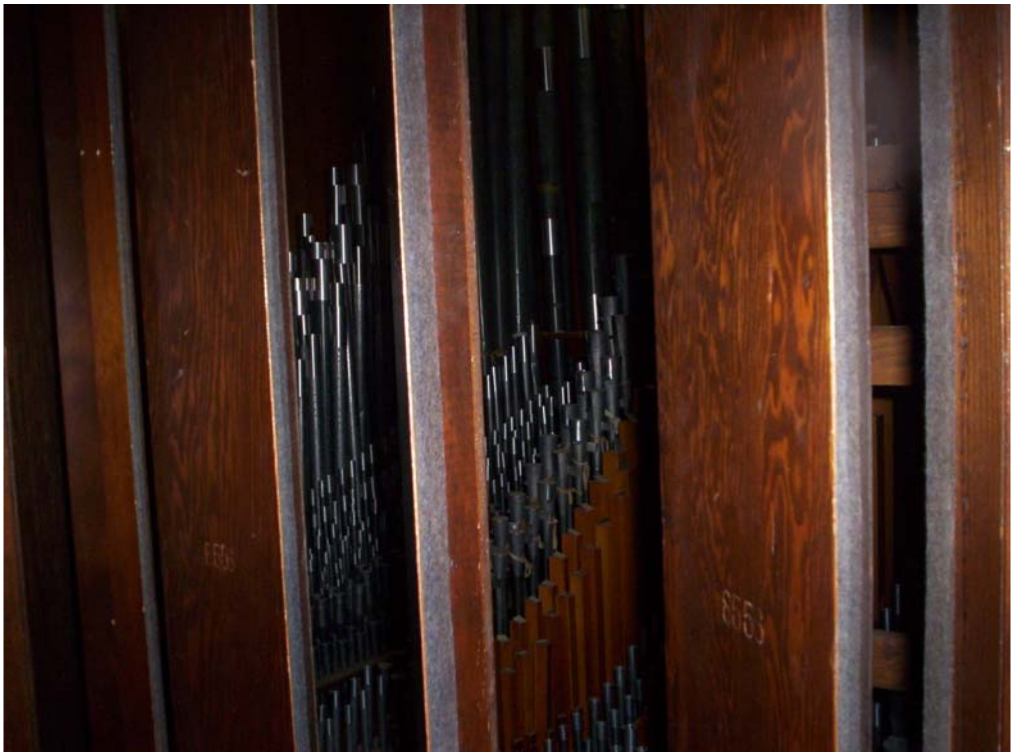

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

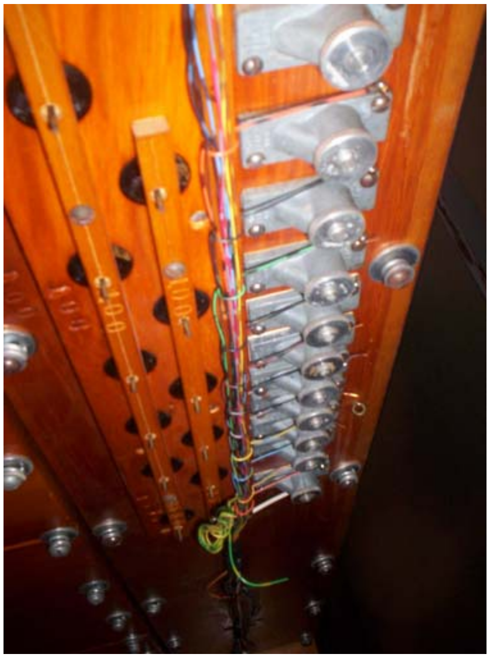

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18