Acoustics of Organ Pipes and Future Trends in the Research

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Knowledge of the acoustics of organ pipes is being adopted in applied research for supporting organ builders.

Introduction

The pipe organ produces a majestic sound that differs from all other musical instruments. Due to its wide tonal range, its ability of imitating the sound of various instruments, and its grandiose size, the pipe organ is often called the "king of musical instruments" (**Figure 1**). The richness and variety of sound color (timbre) produced by a pipe organ is very unique because of the almost uncountable possibilities for mixing the sounds from different pipes. According to the art of sound generation, there are two kinds of pipes in the organ that are similar in function to other wind instruments: flue (labial) pipes and reed (lingual) pipes. Although this article focuses on sound excitation by flue pipes, the role of reed pipes is briefly mentioned (see **Figure 2**). The article also shows how the connection between sound character and pipe shape and dimensions can be understood, and it also considers the trends in the research that focus on helping organ builders in their practical work.

Structure of the Pipe Organ

A sketch of a pipe organ is shown in **Figure 3**. Its main parts are the windchest with the pipes, the wind system, and the control system (keyboard, tracker action, and drawstops; **Figure 2**). The pipes are organized on the windchest according to note and timbre. A set of pipes producing the same timbre for each note is called a rank and each key on a pipe organ controls a note that may be sounded by different ranks of pipes, alone or in combination (see http://acousticstoday.org/organ_stop; for a demo, see http://acousticstoday.org/rank).

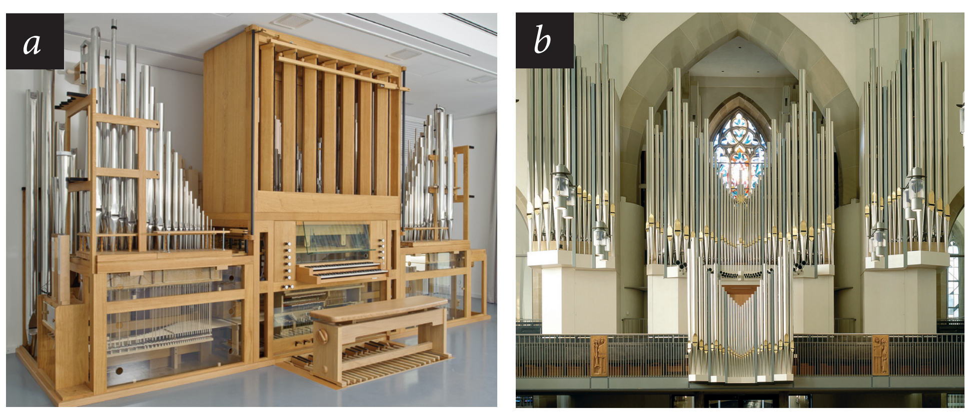

Figure 1. *a: Research organ in the Fraunhofer Institute of Building Physics IBP in Stuttgart, Germany, built by Mühleisen (Leonberg, Germany) in 2011. The pedals can be seen under the bench. Photo by Roman Wack.* ***b:*** *Pipe organ in the Stiftskirche in Stuttgart, Germany, built by Mühleisen (Leonberg, Germany) in 2004. The frontal pipes can be clearly seen. Photo by Theo Holder.*

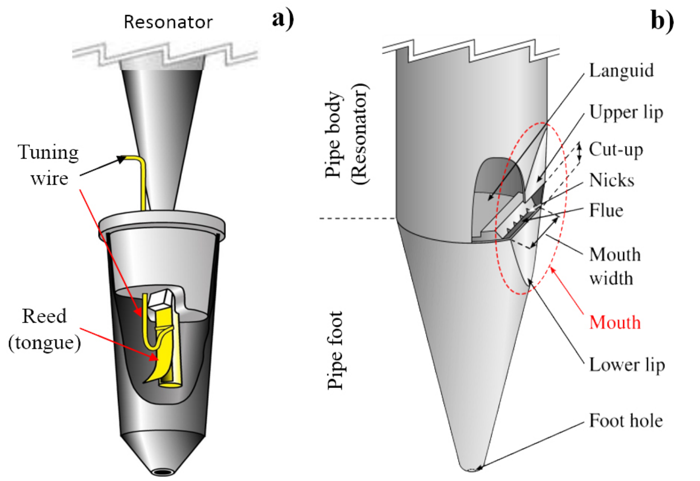

Figure 2. *The parts of a reed (lingual;* ***a****) and a flue (labial;* ***b****) organ pipe. As shown in* ***b****, the cut-up is the distance between the lower and upper lip.*

The ranks can be activated by a drawstop. The so-called slider (**Figure 3**) is a wooden plate that has a number of holes in it, corresponding to the position of the pipes standing in a row. By activating a stop by one of the drawstops, the holes of the slider plate let the air flow from the tone channel into the pipes having the same timbre. All organ pipes produce sound by means of air flowing into the pipe so that each sounding pipe "consumes" a certain amount of air. A tracker action is both the connection between the keys of the keyboard and the tone valves in the windchest (sound tract) and is also the system for switching the stops (registers; register tract). When a key is pressed, the corresponding valve in the pallet box opens and air flows into the tone channel and the pipes selected by the drawstops. When the key is released, a spring closes the valve, blocking the airflow.

The pressurized air is provided by the wind system that consists of four essential parts. (1) The blower (electrical fan) is the air supply of the instrument. The blower pumps air into the wind system according to the "wind consumption" of the instrument. (2) The roller valve regulates the airflow from the blower into the bellows. (3) The bellows ensure that the pressure in the windchest remains constant. The required pressure of the wind in the pipe organ is set by the organ builder by placing weights on the top of the bellows. (4) Finally, the wind duct connects the wind system with the pallet box (lower part of the windchest), thereby providing the air supply for the pipes. In large pipe organs, multiple wind systems can be present and operate at the same time, but each provides air to a different set of ranks.

As mentioned above, there are two kinds of pipes that are similar in function to other wind instruments: flue (labial) pipes (like a recorder or a transverse flute) and reed (lingual) pipes (like a clarinet or a saxophone). The sound of a reed pipe is produced by a vibrating brass strip known as a reed (tongue). Air under pressure (wind) is directed toward the reed that vibrates at a specific pitch. This is in contrast to flue pipes, which contain no moving parts and produce sound solely through the vibration of air (see **Figure 2**). In a typical pipe organ, there are considerably more flue pipes than reed pipes. The main parts of a reed and a flue pipe are shown in **Figure 2**.

In the next sections, the physics of flue pipes is discussed. The discussion is based on an earlier publication (Miklós and Angster, 2000) complemented by certain results of European research projects carried out in cooperation with several organ builder enterprises. In this paper, the reed pipes won't be examined (but see Fletcher and Rossing, 1991; Miklós et al., 2003, 2006).

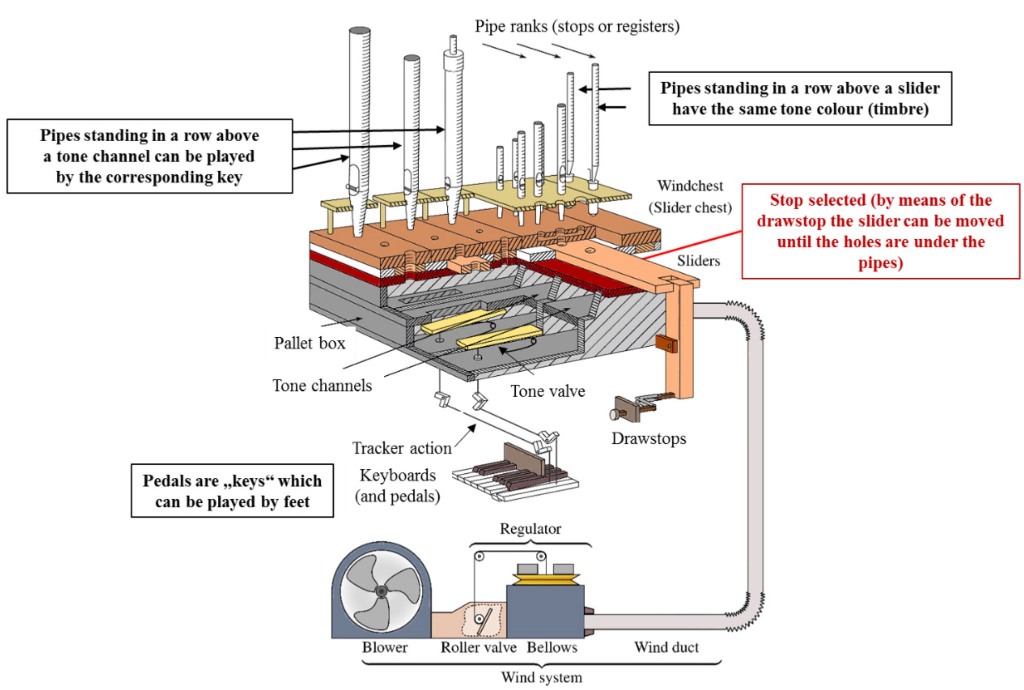

Figure 3. *A sketch of a pipe organ and its most important parts.*

Flue Pipes

Although the main features of the sound of flue organ pipes have been investigated extensively (Yoshikawa and Saneyoshi, 1980; Verge et al., 1994; Fletcher, 1996), the connection between sound character and pipe shape and the dimensions are still not well understood. In the tradition of organ building, however, the sound character of the different ranks is unambiguously associated with pipe shape, material, and dimensions (Töpfer, 1888; Mahrenholz, 1987). Although the timbre, and especially the speech (attack) of the pipe (the very beginning of the pipe sound), may be changed significantly by voicing adjustments (changing the geometrical parameters of the pipe such as the diameter of the foothole and the width of the flue and cutting up the mouth [upper lip]), the main characteristics of the sound are quite stable for a given rank and primarily depend on the form and progress of dimensions with note (scaling) of the pipes. It is of interest to scientists that only a very narrow range of all the possible dimensions (diameter, wall thickness, cut-up height, flue width) and materials are actually used for organ pipes. Some of these limitations can be explained by technological reasons, but most of them have no basis in science.

Experimental Results

Although flue pipes offer a very wide variety of sounds, the measured properties of these sounds contain several common elements that can be used to characterize them. To determine such characteristics, three measurements are used: the stationary spectra (the spectrum of the sound of a continuously sounding pipe) at both the mouth and the open end and the attack transient at the mouth. To do this, stationary spectra are measured by microphones placed close (~3-5 cm) to the two openings of the pipes and the attack transients at the mouth are analyzed using a special computer program (Angster and Miklós, 1995).

Steady-Sound Characteristic Features and Related Physical Phenomena

The stationary spectra of a flue pipe and the characteristic features of the sound spectra can be seen in **Figure 4**.

The flue pipe ranks are divided into three groups according to their characteristic sound. The widest flue pipes (flutes) produce tones with the most fundamental and the least harmonics among flue pipes, and they start to speak the fastest

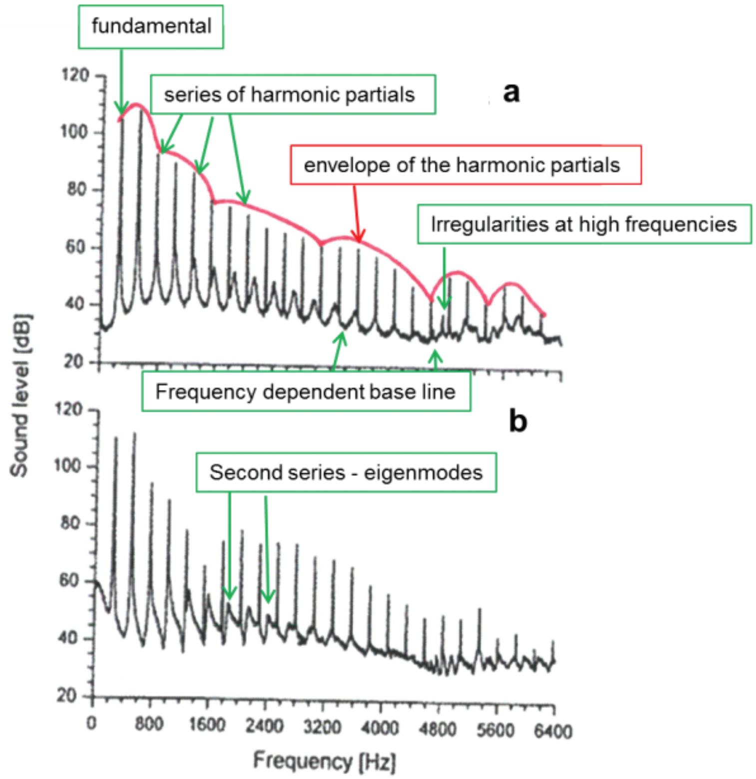

Figure 4. *Typical stationary spectrum of a flue organ pipe at the open end (a) and at the mouth (**b**). See text for details.*

(fast attack). The Diapason or principal family produces the characteristic sound of the pipe organ and is not intended to imitate any other instrument or sound. They are medium scaled and are often prominently featured in the façades of pipe organs. They can be characterized by their strong second partial, especially in the attack. String pipes are the narrowest flue pipes. They produce a bright sound that is low in fundamentals and rich in upper partials. One of the most common string stops is named Salicional. String stops are often named after bowed string instruments such as the Violoncello, the Gamba, and the Geigen (from the German Geige, for violin; see http://acousticstoday.org/flue). They have very bright sounds with more than 20 harmonic partials but with a slow attack (Miklós and Angster, 2000).

The characteristic features of the sound spectra of a flue organ pipe can be listed and the related physical phenomena can be explained as follows.

A Series of Harmonic Partials

It is well-known from the elements of the Fourier theory (Korn and Korn, 1975) that the spectrum of a periodic signal contains a series of harmonic components (partials). These partials can be seen in **Figure 4**.

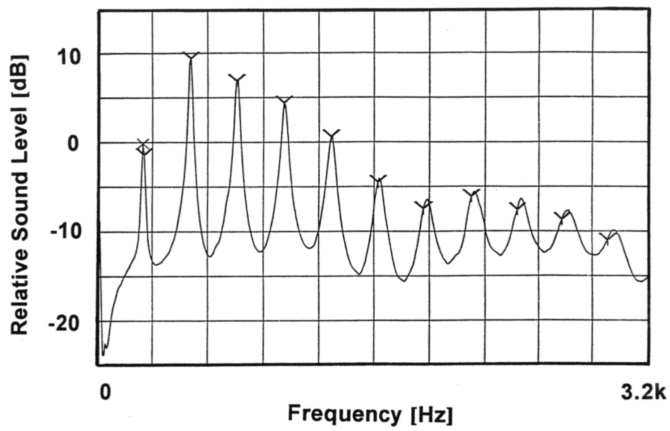

Figure 5. *Eigenresonances of a tube that is 60 cm long and 31 mm in diameter. The harmonic partials are marked by v-shaped cursors.*

A Second Series of Smaller and Wider Peaks That Are Not Harmonically Related But Are Slightly Stretched in Frequency

The small, broad peaks shown in the spectrum demonstrate the presence of acoustic eigenmodes (standing waves) of the pipe. (A so-called standing wave occurs in a pipe when the sound waves reflected back and forth in the pipe are combined such that each location along the pipe axis has constant but different amplitude. The locations with minimum and maximum amplitude are called nodes and antinodes, respectively. The frequency of the standing wave is the resonance frequency or eigenfrequency of the tube. Standing waves occur in a tube on several frequencies.) The presence of eigenmodes can be tested experimentally by using external acoustic excitation. If a pipe is placed in the sound field generated by a loudspeaker, the pipe will amplify the frequency components that correspond to the eigenresonances. Placing a small microphone in the pipe and using an excitation in a wide frequency range, the eigenresonance spectrum can be determined. Such a spectrum is shown in **Figure 5** for a cylindrical tube. The eigenresonances are slightly stretched; the eigenfrequencies are a bit higher than the harmonics of the first eigenresonance.

The stretching of the eigenfrequencies is much more pronounced in open organ pipes. In the spectrum of a Diapason pipe (**Figure 4a**), the ninth eigenresonance lies about halfway between the ninth and tenth harmonic partials. The stretching becomes larger for larger diameter-to-length ratios and for smaller openings at the pipe ends. The measured spatial distribution of the first, third, and fifth eigenmodes in a fairly wide flute pipe is shown in **Figure 6**. It can be observed that the standing waves lay asymmetric in the pipe; they are shifted toward the mouth. Moreover, the half wavelength of the first eigenmode (and *n* times the half wavelength of the *n*th eigenmode) is longer than the length of the resonator. The difference can be regarded as an "end correction" for practical calculations.

These experimental facts can be understood by taking into account the physical properties of the organ pipe as an acoustic resonator. The air column in the pipe has several eigenmodes (standing wave patterns) with characteristic resonance frequencies (eigenfrequencies). Their frequencies are not harmonically related because of the end correction (Nelkon and Parker, 1970), which decreases with the frequency (Fletcher and Rossing, 1991). Because the end correction is proportional to the pipe diameter, the stretching of the eigenfrequencies is larger for wide pipes than for narrow ones. Moreover, the end correction for a small opening (mouth) is larger than that of the larger open end. Therefore, the eigenfrequency stretching of an organ pipe is larger than that of a tube with the same length and diameter. Because of the different end corrections at the openings, the standing wave is located asymmetrically inside the organ pipe (Angster and Miklós, 1998). Therefore, the sound spectra at the mouth and at the open end are different, as shown in **Figure 4**.

A Frequency-Dependent Baseline

The baseline of the spectrum (see **Figure 4**) is determined by the broadband noise at the mouth of the pipe. This noise is produced by the airflow at the flue and the upper lip (Fabre et al., 1996). Because the resonator amplifies this noise around the eigenresonances, the amplified noise may dominate the sound of the pipe in the high-frequency range,

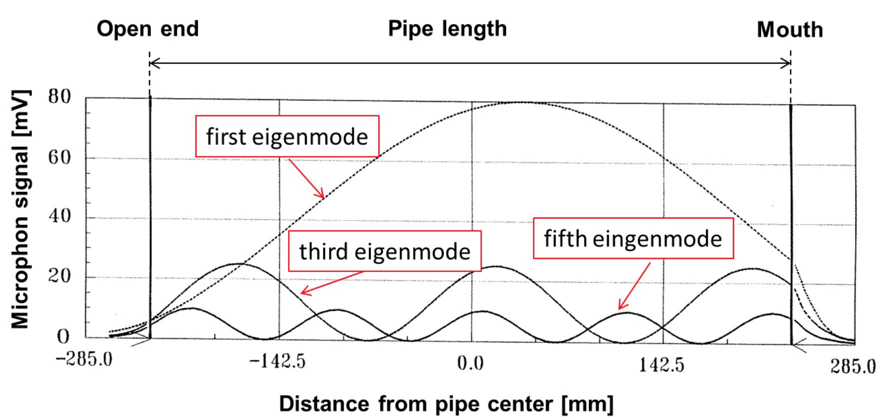

Figure 6. *Standing waves in an organ pipe. Sound pressure distributions of the first, third, and fifth eigenmodes in a wide pipe are shown.*

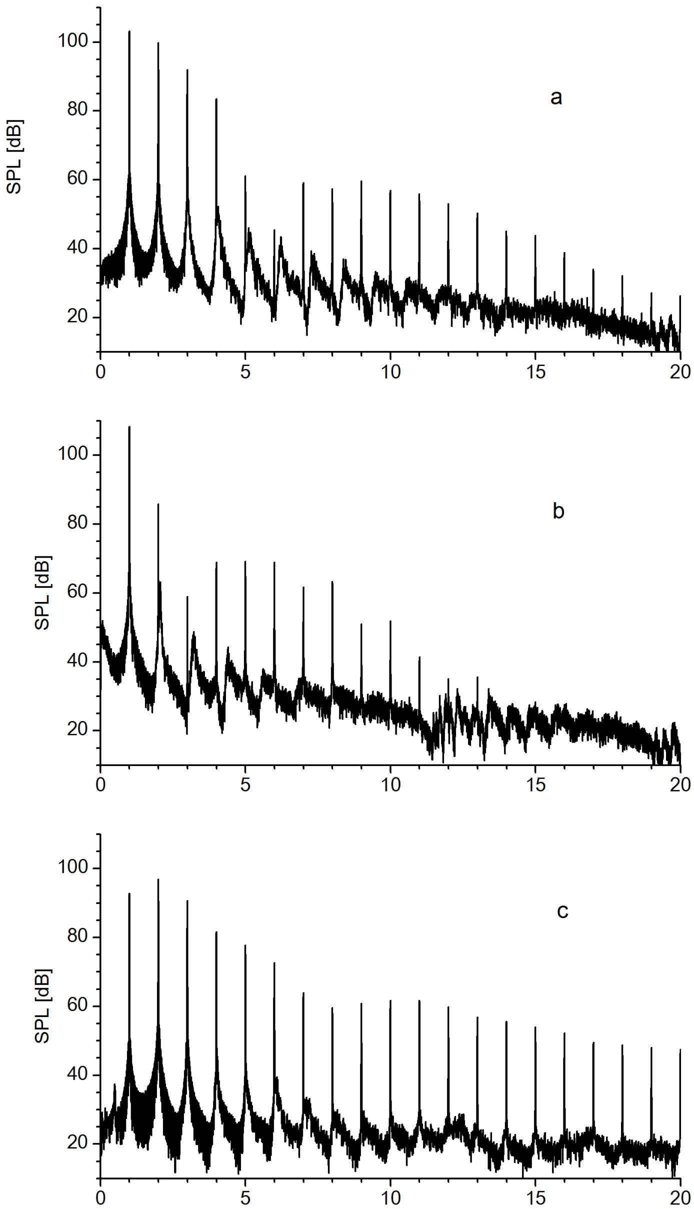

*Figure 7. Measured spectra of a Diapason (normal; **a**), a Flute (wide; **b**), and a Salicional (narrow; **c**) pipe.*

where the partials of the fundamental are usually weak. The high-frequency noise content can be very effectively reduced by nicking, e.g., cutting grooves in the languid (metal plate separating the pipe foot and the pipe body; **Figure 2**; Angster et al., 1997). This method can increase the ratio of the harmonic partials to the baseline very significantly.

Envelope of the Harmonic Partials

The form of the envelope depends on the total losses in the pipe that include the volume losses in the air, the surface losses at the pipe wall due to viscosity and heat conduction, the radiation losses at the openings, and the energy loss due to the coupling of the sound to the wall vibrations. For organ pipes, the surface and radiation losses are much larger than the other two effects. At the same frequency, the surface losses are relatively larger and the radiation losses are relatively smaller for narrow pipes than for wide pipes. Because the surface losses decrease and the radiation losses increase with the frequency, a loss minimum occurs at a certain frequency. Indeed, such a loss minimum can be observed in narrow pipes. Looked at in another way, the largest amplitude occurs not for the fundamental but for a higher partial. Measured sound spectra of a normal, a wide, and a narrow pipe are shown in **Figure 7**. In the case of wide/narrow pipe resonators, there are less/more partials, respectively, than by the normal pipe resonator.

Radiation losses occur through sound radiation at the pipe openings (mouth and open end). Because the openings are much smaller than the wavelength of the sound, both of the pipe openings can be regarded as simple sources (monopoles; Angster and Miklós, 1998). Measurements by an acoustic camera system confirm this simple source model (Angster et al., 2011). **Figure 8** shows that the sources of the sound are really the openings at the mouth and at the open end of the pipe. Based on the recording of the first partial (fundamental) in **Figure 8a** (see http://acousticstoday.org/8a.mp4) the sound is radiated in phase but with different intensity. The sound pressure is larger at the mouth. **Figure 8b** (see http://acousticstoday.org/8b.mp4) shows that the two sources radiate in opposite phase. The simple source at the mouth is usually much stronger than the source at the open end.

The envelope of the harmonics of the sound spectrum at the mouth shows a formant-like structure with a conspicuous minimum (see **Figures** 4b and 7) because of the relative position of the harmonic partials and the neighboring eigenmodes. Due to the stretching of the eigenfrequencies, the harmonic partials are gradually shifted from the peaks of the eigenmodes into the valley between them and then further toward the peak of the neighboring lower eigenmode. If the harmonic frequency is close to the eigenfrequency, the partial will be amplified by the eigenresonance. A harmonic partial lying midway between two eigenmodes will not be amplified while the partial closest to the minimum between two eigenmodes will be the smallest one. Thus, a formant minimum can be observed in the spectra measured at the mouth. Because the stretching is more pronounced for wider pipes, the position of the formant minimum depends on the diameter-to-length ratio of the pipe. Sound spectra mea-

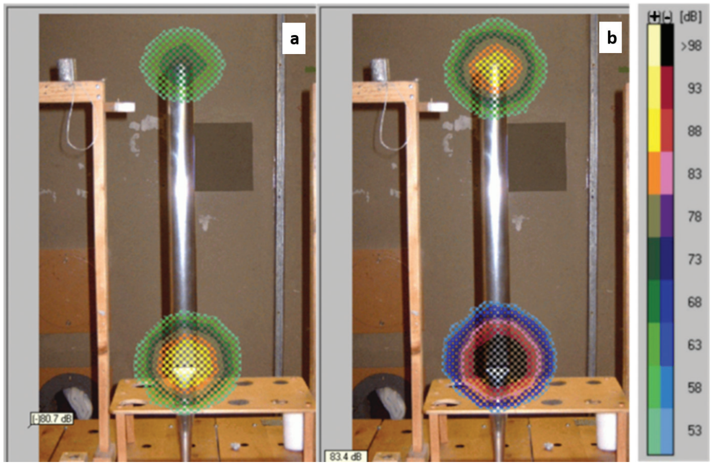

Figure 8. *Sound radiation on the first (a) and second (b) partials. The colors correspond to the intensity of the sound (see http://acousticstoday.org/8a.mp4 and http://acousticstoday.org/8b.mp4).*

sured at the mouth of a normal (Diapason), a wide (Flute), and a narrow (Salicional or string) pipe clearly show this effect (**Figure 7**). For the Diapason pipe, the first minimum lies at the sixth partial (**Figure 7a**). For the Flute pipe, the minimum occurs around the third partial (**Figure 7b**); for the Salizional pipe, it is shifted up to the eighth partial (**Figure 7c**).

Different Spectral Envelopes at the Mouth and at the Open End

It has been shown that the radiated acoustic field corresponds to that of two simple sources located at the openings of the pipe (see **Figure 8**). The simple sources radiate in phase for the odd partials and out of phase for the even partials. The strength is different for both sources, and the two openings radiate different spectra (Angster and Miklós, 1998). The spectra of the sound radiated at the openings are different because the standing waves in the pipe are asymmetrically located (see **Figures 4** and **6**). Because the end correction is inversely proportional to the area of the opening (Angster and Miklós, 1998), the envelope minimum occurs for the lower partial at the mouth than at the open end. That is, the spectral envelopes at the mouth and open end are always different.

Irregularities in the High-Frequency Part of the Spectrum

Irregularities in the range of higher harmonics can be caused by the excitation of transverse resonances (cross-sectional eigenmodes) of the pipe. Pipe ranks may have harmonic partials in the range of transverse resonances; therefore, the transverse resonances can appear in the spectrum between the harmonic partials (**Figure 7b**, first transverse resonance around the eleventh partial). These resonances are excited by the high-frequency noise at the upper lip.

Irregularities in the spectrum may also be caused by wall vibrations. It has been shown that wall vibrations cannot radiate sound directly (Backus and Hundley, 1965; Angster et al., 1998). On the other hand, a linear coupling exists between the air column and the pipe wall for rectangular pipes (Angster et al., 2011) and also for cylindrical pipes if the pipe cross section is not a perfect circle but is slightly elliptical or the wall is very thin (Kob, 2000). In these cases, wall vibrations can influence the sound radiated at the openings, especially during the transient (Angster et al., 1998; Kob, 2000). If a sharp vibration mode is close to an eigenmode or harmonic partial of the pipe sound, both modes will be coupled, which leads to a slight detuning of the corresponding sound component. Nevertheless, such a coincidence is quite rare in practice.

Figure 9 shows the vibration diagrams recorded by a three-dimensional (3-D) laser vibrometer of a Diapason G pair of pipes. **Figure 9a** (http://acousticstoday.org/9a.mp4) shows the pipes made of plain metal (tin-lead alloy) at the fifth partial (974 Hz) and **Figure 9b** (http://acousticstoday.org/9b.mp4) shows the pipes made of zinc at the fifth partial (same frequency). It is evident that despite the same measuring frequency, the pipes made of different materials show very different vibration mode shapes. **Figure 10** shows the 3-D representation of the analyzed attack transients (attack; how the partials will be built up in time) of the same Diapason G pair of pipes (shown up to the sixth partial), and the noises between the partials are also recorded. It is obvious that the attacks of the two pipes are very similar. Experiments showed that the differences in the recorded attacks with pipes made of different materials are not larger than with two successive attacks of the same pipe.

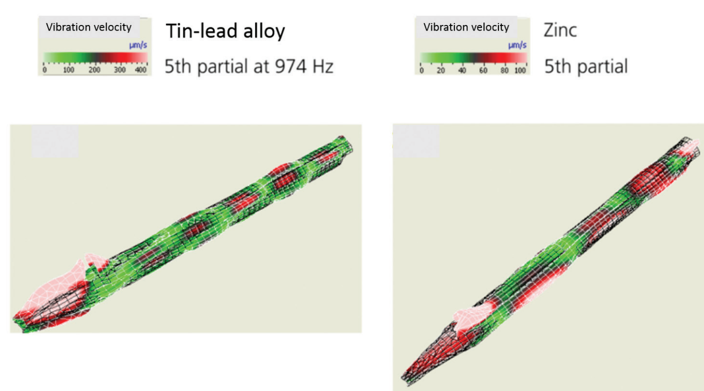

Figure 9. *Vibration-mode shape of the Diapason G pair of pipes. Red indicates that the pipe walls are vibrated hard and green means less vibration. a: Pipe made of plain metal (tin-lead alloy) at the fifth partial (974 Hz, see http://acousticstoday.org/9a.mp4). b: Pipe made of zinc at the fifth partial (and same frequency, see http://acousticstoday.org/9b.mp4).*

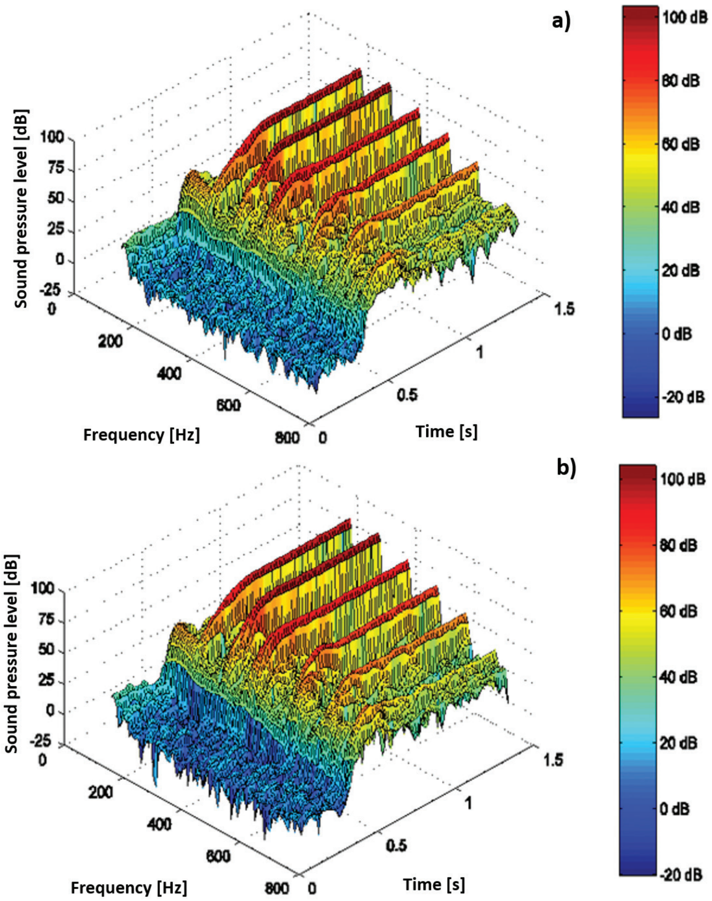

Figure 10. *A 3-D representation of the analyzed attack transients of the Diapason G pair of pipes (same as shown in* ***Figure 9****). The graph shows the onset of the pipe sound and thus how the partials of different frequencies are built up in time.* ***a****: Made of plain metal (tin-lead alloy).* ***b****: Made of zinc.*

The explanations given above show that several different mechanisms influence the steady sound of pipes. On the other hand, even the most complicated features could be assigned to the measurable and understandable physical properties of flue organ pipes.

The research results in flue pipe acoustics can be adapted in the applied research for supporting the daily work of organ builders. The next section presents an example of the trends in applied research.

Sound Design of Chimney Pipes

Chimney pipes are semiopen flue organ pipes whose resonator consists of two main parts: a straight cylindrical main part and a shorter and thinner chimney attached to its top (**Figure 11**, *top left*). The length and the diameter of the chimney may vary, and this makes it possible for the organ builder to adjust the timbre. For example, chimney pipes in baroque-style pipe organs should have a sound rich in the pure fifth (third harmonic), while romantic-style instruments require more major third (fifth harmonic) in the sound. To be able to fulfill these requirements, special design rules are needed for determining the dimensions of the pipes so that the desired character of the sound can be achieved. The process of determining the appropriate geometrical dimensions of organ pipes with the purpose of attaining a predefined timbre is referred to as "sound design."

The chimney pipe construction was studied by different researchers, most notably Helmholtz. His conclusion was that to reinforce the fifth harmonic in the sound, it is best to have a chimney with a length two-fifths of that of the main resonator (Helmholtz, 1954). Apparently, in a more recent examination, the configuration proposed by Helmholtz turned out to be the least favorable one (Kokkelmans et al., 1999). In the study initiated by the organ builders and performed by the authors of this article, a novel methodology for the sound design of chimney pipes was established and implemented in a software tool.

The idea of the proposed sound design approach is to tune the eigenfrequencies of the resonator so that they become coincident with the frequencies of predefined harmonic partials of the sound (Rucz et. al., 2013). When a harmonic partial overlaps with an eigenfrequency, the corresponding eigenmode gets excited very efficiently and hence the amplification of the harmonic can be expected.

By computer simulation, the so-called input admittance is calculated. The peaks of the input admittance correspond to the peaks of eigenresonances. It is important that the peaks of the red curves in **Figure 11** match the partial to be enhanced.

The measured steady-state sound spectra are displayed in **Figure 11a-c**. In each diagram, the sound pressure measured at the pipe mouth and the calculated input admittance are displayed by the black and red lines, respectively. **Figure 11a** shows the reference pipe with the amplitude of the first seven harmonics, indicated by the numbers on the blue background. The reference pipe has a strong fundamental component in its sound while the higher harmonics are very weak. **Figure 11b,c** displays the results of the chimney pipes optimized for the third and fifth harmonics, respectively. The numbers on the green background indicate the amplification of the targeted harmonic partial compared with the levels measured in the case of the reference pipe. The num-

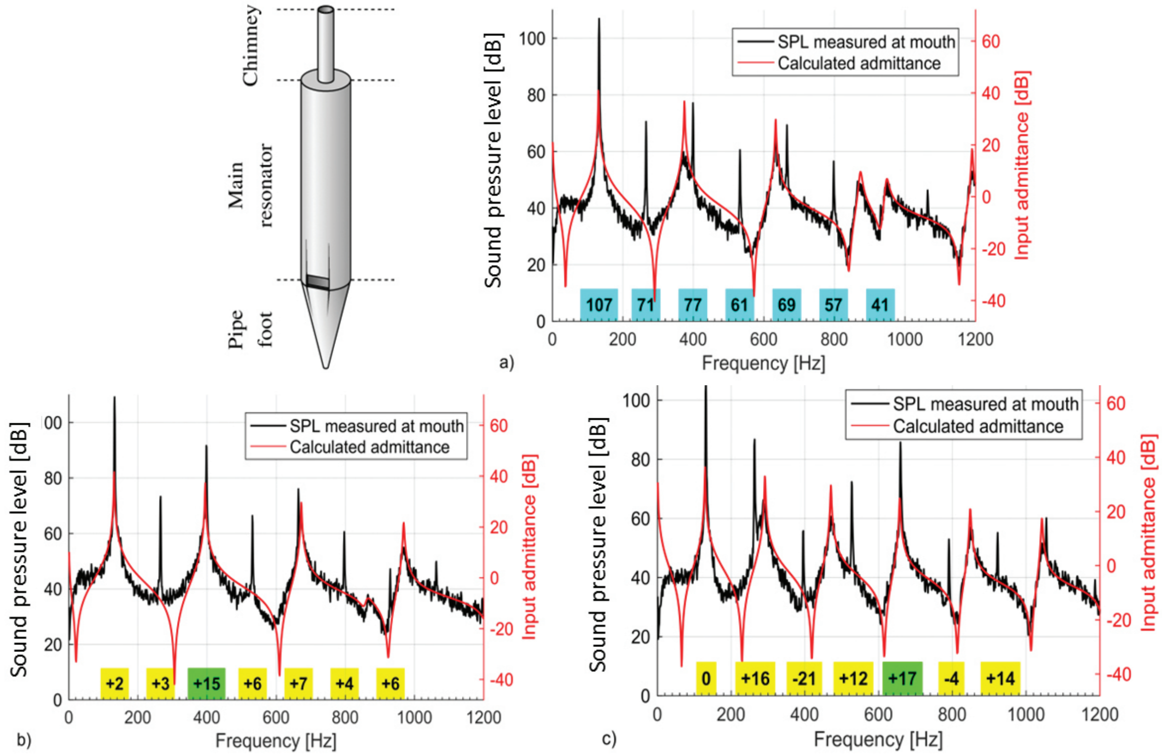

Figure 11. *Top left: sketch of a chimney organ pipe.* ***a–c:*** *Measured spectra (black) and calculated input admittance (red) of the experimental chimney pipes.* ***a****: Reference chimney pipe design. Numbers on the blue background are the amplitudes of the first seven harmonic partials.* ***b****: Optimized design enhancing the third harmonic (pure fifth) by 15 dB.* ***c****: Optimized design enhancing the fifth (major third) by 17 dB. Numbers on the green and yellow backgrounds show the relative levels of the harmonics compared with the reference pipe.*

bers on the yellow background show the same changes in the levels of the other harmonics. As can be seen, the optimized resonators can enhance the targeted harmonics by more than 15dB while keeping the fundamental frequency constant. This amplification can be considered substantial if one takes into account that the experimental pipes only differed in the geometry of their resonators.

Conclusions

The intention of the authors of this paper was to demonstrate that the research on organ pipes leads to a better understanding of how they function. Moreover, research can provide scientific explanations to support or refute strong established beliefs of organ builders and, last but not least, can provide new scientific results and tools for further improvement of the art of pipe organ building.

Biosketches

Judit Angster is a physicist and has been working at the Fraunhofer Institute of Building Physics IBP in Stuttgart, Germany, since 1992. She established and has been head of the Research Group of Musical Acoustics/Photoacoustics. She lectures on acoustics at the University of Stuttgart and the State University of Music and Performing Arts Stuttgart. Her research activities are focused on musical acoustics, music and room, pipe organ acoustics, and photoacoustics. She organizes organ acoustics workshops as an international advanced training for organ builders and organ experts. She comes from the well-known organ builder family Angster.

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András Miklós is a physicist whose main interests are photoacoustics, musical acoustics, and theoretical and solid-state acoustics. He was a senior scientist at the University of Heidelberg, Heidelberg, Germany. He has been director of the Steinbeis Transfer Center Applied Acoustics in Stuttgart, Germany, since 2003. Since 1986, he has carried out pipe organ research with Judit Angster and has taken part in the international advanced training courses at the Fraunhofer Institute of Building Physics IBP in Stuttgart, Germany.

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