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25 years applied pipe organ research at Fraunhofer IBP in Stuttgart

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Abstract

Throughout the world, musical instruments are deeply rooted in cultural traditions. They are part of our cultural heritage, and their preservation and further development deserves our utmost attention. For many years, the Fraunhofer Institute for Building Physics IBP has been engaged in the research of European musical instruments, the pipe organ in particular. To preserve its sound, to give support in building instruments as well as to contribute to the further development by integrating modern technologies are the focus of the joint research with other research institutions and a multitude of European organ building enterprises.

In 25 years, 9 common European and several other research projects were carried out. Some examples of the topics will be mentioned like development of 1) different kinds of new wind systems, methods and software for the design, 2) design methods, tools and software with applying computer simulations for flue and reed organ pipes, 3) innovative swell shutters, 4) design methods and comprehensive tools for matching the instrument on the acoustics of the room. The procedure of research, way of communication with instrument builders, the method of demonstration and dissemination of the research results will be discussed.

Keywords: Music, Pipe organ, acoustics

1 INTRODUCTION

The Research Group of Musical Acoustics of the Fraunhofer IBP in Stuttgart, Germany deals mostly with pipe organ research [1–6]. The manufacturing of pipe organs is a traditional European industrial sector, which should be preserved. Nevertheless, innovative design methods and technologies can be applied in the daily practice, without endangering the valuable traditions. As Judit Angster comes from a well-known organ builder factory "Josef Angster and Son" [7, 8], she decided to help the small organ builder enterprises in Europe to overcome their practical problems. Organ builders are artisans, who do not have the capacity to consider and treat an instrument as a complex physical system to be able to surmount special problems. Thus the main goal of the research and development work at the IBP has been to carry out applied research so that the results can directly be used in practice. Nonetheless, fundamental research also had to be carried out to be able to focus then on the application.

2 WAY OF COMMUNICATION WITH INSTRUMENT BUILDERS

The first challenge when trying to set up a research project in cooperation with instrument builders is the "translation" of the practical problems to the "language" of scientific research. The instrument makers explain their problems from the viewpoint of the practical work. Acoustical phenomena will be described by artistic expressions. The issues have to be formulated in a special scientific way so that the answers to the questions raised can be given by means of scientific research. This is always a pretty hard mission to accomplish in a project application. Furthermore, one has to be careful during the implementation of the work so that the instrument maker partners can understand how research has to be done. Otherwise the project partners—who generally support the work—lose the sense of the participation.

Generally it is "easy" to solve physical problems by means, as an example, of solving differential equations. Nevertheless you never can report for an instrument maker about such theoretical solutions. Hence the next step is to translate the research results to the language of the craftsmen. Doing so by meetings, organ builders have been amazed about how physics can be so simple and understandable. That's why it became possible to carry out several research projects with numerous European organ builder firms [9].

There appears a disadvantage by such applied research projects. The applicable results are owned by the enterprises and so they should not be published for several years after finishing the work. For this reason the authors of the present paper plan to summarize the most important outcomes of earlier confidential European projects in a book. Nevertheless, the dissemination of knowledge has been carried out as soon as possible in the form of workshops organized for organ builder enterprises. These workshops have been the only possibility internationally for organ builders to learn about the acoustics of the organ and getting instructed for the application of research results, design methods, and software.

3 EXAMPLES OF RESEARCH TOPICS

3.1 Scaling of labial organ pipes

In organ building, pipe scaling is a complicated process. All geometrical dimensions of a labial pipe, such as diameter, flue width, cut-up etc. (Figure 1), have to be determined so that its sound fulfills the requirements defined by the organ builder: each pipe stop (consists of about 60 pipes with the same sound character, e.g. “Diapason”, “Chimney flute”, “Salicional”) has a characteristic timbre that should be balanced and clearly recognizable over the whole rank from low to high notes. Sound at the audience position, however, is strongly influenced by room acoustics. When planning an organ, the organ builder judges the specific room properties and determines all pipe diameters needed for an adequate sound power. Then, a uniform volume and sound distribution is hopefully achieved when playing the organ. If a room amplifies low and dampens high frequencies, for example, the diameters of low pipes and thus their sound power have to be decreased and those of high pipes have to be increased in order to balance the influence of the room [10, 11].

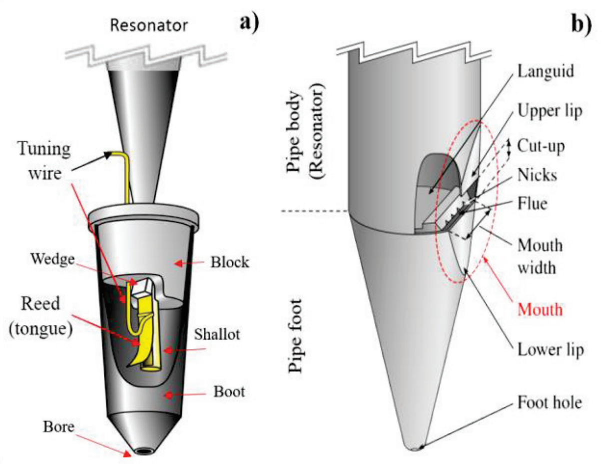


Figure 1. The parts of a reed (lingual) **a)** and a flue (labial) **b)** organ pipe.

3.1.1 Scaling of chimney pipes

Chimney pipes are semi-open 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 2a). The length and the diameter of the chimney may vary, which allows the organ builder to adjust the timbre of the pipe. 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.”

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. Acoustic measurements have been carried out in the anechoic chamber of the Fraunhofer IBP in Stuttgart (Figure 3).

The idea of the proposed sound design approach is to tune the eigenfrequencies of the resonator such that they become coincident with the frequencies of predefined harmonic partials of the sound [12, 13]. The eigenfrequencies of the resonator have been specified by means of a transfer function measurement as shown in Figure 2b. 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 (i.e., the ratio of the acoustic volume velocity and the acoustic pressure at the mouth of the pipe) is calculated [12]. The peaks of the input admittance correspond to the peaks of natural resonances.

The performance of the developed software tool was tested by building experimental chimney pipes with the dimensions calculated by the software and by comparing their measured sound spectra with the results of the computer simulations. The measured steady state sound spectra and the calculated input admittances are displayed in Figure 4a–c. In each diagram, the sound pressure spectrum measured at the pipe mouth and the calculated input admittance are displayed by the black and red lines, respectively. The broad peaks in the sound spectra correspond to the natural acoustical resonances of the pipe, while the sharp peaks are the harmonic partials of the pipe sound. The design method is successful when one of the peaks of the red curves in Figure 4b–c matches the partial to be enhanced.

Figure 4a shows the sound spectrum of the reference pipe (a chimney pipe with the usual dimensions) 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 4b and c display 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 numbers 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 15 dB while keeping the fundamental constant. This amplification can be considered substantial if one takes into account that the experimental pipes only differed in the geometry of their resonators. The developed software tool is being used in the practical work of the organ builder partners of the project [14].

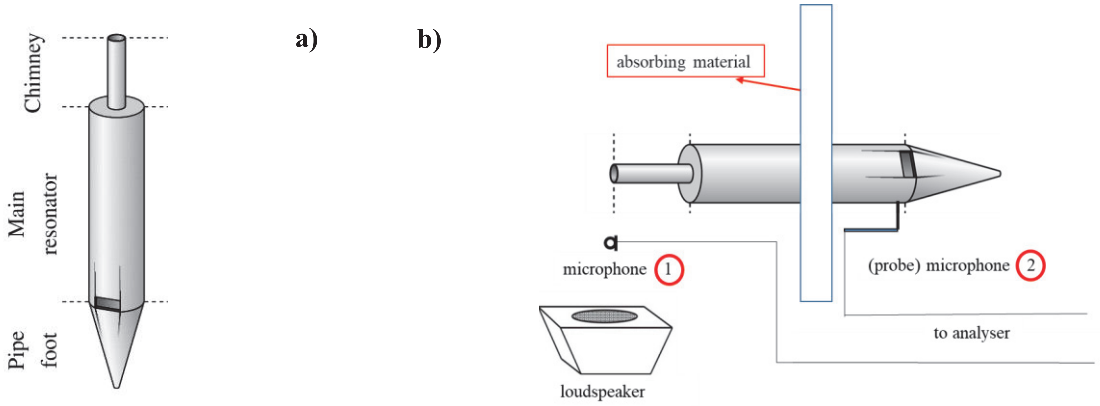


Figure 2. a) Sketch of a chimney organ pipe. b) Measurement of the transfer function: the pipe resonator was excited by a loudspeaker; (probe) microphone 2 is in the resonator against the pipe mouth

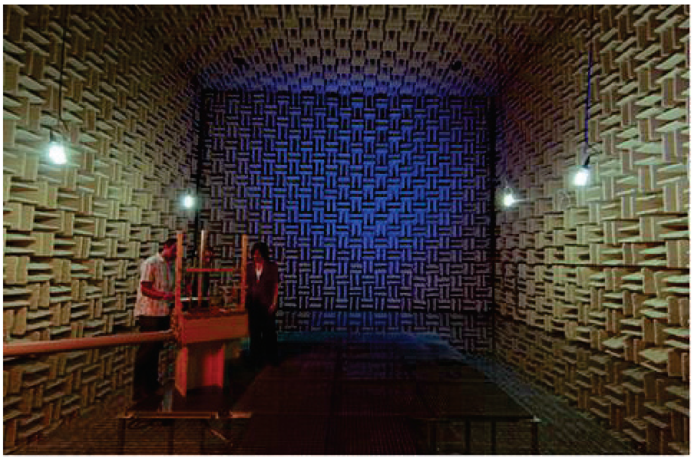


Figure 3. Acoustic measurements in the anechoic room of the Fraunhofer IBP in Stuttgart

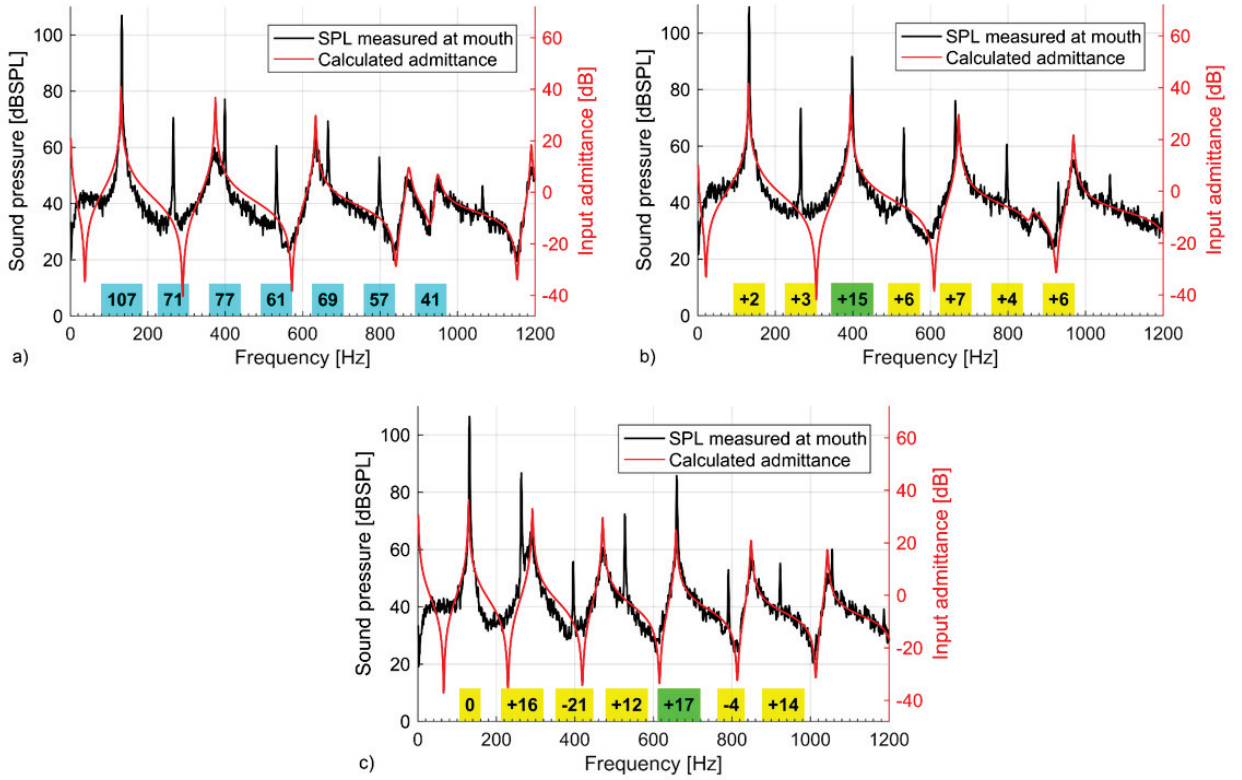


Figure 4. **a–c)** Measured spectra (black) and calculated input admittance (red) of the experimental chimney pipes. **a)** Reference chimney pipe design. Numbers on the blue background are the amplitudes of the first seven harmonic partials. **b)** Optimized design enhancing the third harmonic (pure 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.

3.1.2 Scaling of wooden pipes

Research partners in the European research projects wanted to build the large wooden pedal pipes narrower than so far without deteriorating the character of the sound. Frequently, there is only little space for these pipes. Moreover, in the case of narrower pipes, the wind chest could be built in shorter form and thus in a more cost-efficient manner. Wooden pipes always have a rectangular cross section. Their mouth widths (= pipe widths) are equal to those of the reference pipes (circular metal pipes with the same pitch and similar timbre). Their depths are traditionally calculated such that the rectangular cross section $A_{w,trad}$ equals the circular cross section A_{ref} of the reference pipes (Figure 5a). As mentioned before, the widths become too large sometimes so that the total width of a whole pipe rank does not fit into the available space within the organ. Therefore a new calculation method was developed. Here the organ builder first scales down the widths until the pipe rank fits into the available space. In order to avoid an essential change of the timbre, their depths are then calculated, such that instead of the cross sections the energy losses or quality factors Q (Figure 5b) of the traditional and new wooden pipes become equal [10, 14].

The new calculation and design method was tested by building and measuring experimental pipes, proving the applicability of the proposed method. Thus, it is now possible to build narrower wooden flue pipes which maintain the sound quality of the pipes with standard dimensions.

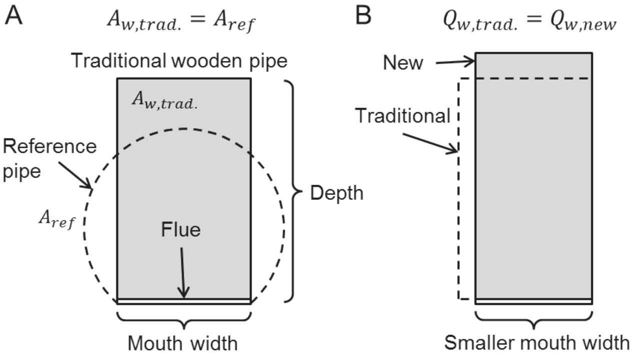


Figure 5. A: Traditional scaling of wooden pipes with equal cross sections, B: innovative scaling of wooden pipes with equal losses (quality factors).

3.2 Scaling of reed (lingual) organ pipes

The sound generation mechanism of reed organ pipes is a complex physical phenomenon. The reed pipe consists of three main parts: the boot, the block with the shallot and the reed, and the resonator, as it is depicted in Figure 1a. When the pipe is played air flows through the bore and the reed is forced into motion by the pressure forces acting on it. Under playing conditions the motion becomes periodic by means of an aerodynamic-acoustic feedback loop [15].

The pitch of the pipe is determined by the coupling of two oscillating systems, the vibrating reed and the acoustic resonator-shallot system [16]. The strength of the coupling varies in a wide range for different pipe ranks. Trumpet pipes are characterized by strong interaction between the resonator and the reed, whereas in case of stops such as the Vox humana the coupling is weak typically. In both cases, the resonator has a great effect on the timbre of the pipe. In case of weak coupling the resonator acts as a filter, which can reinforce or suppress certain harmonic partials in the pipe sound.

Discussions with organ builder partners in the framework of a European project [17] have shown that there are no common rules for the design of reed pipe resonators. Also measurements prove that design rules of thumb applied currently in practice do not fully exploit the capabilities of the resonator. Thus, the aim of our research has been to achieve an optimal scaling of reed pipe resonators, which can lead to cost and effort reduction in practice. Therefore a methodology has been committed, which combines a onedimensional analytical model with three-dimensional finite element simulation in order to predict the acoustic behavior of reed pipe resonators. The proposed method is validated by means of comparisons with measurements and it is shown that the technique is capable of calculating the eigenfrequencies of the resonator accurately [18].

As an example the scaling method of reed pipes is presented on a “Vox humana” pipe, which imitates the human voice. This is a so-called beating lingual pipe, as by sounding the reed (tongue) beats periodically on the shallot. The resonator consists of three sections (Figure 6a):

1. the shallot continues in a straight neck, which has a length of 2/5 of that of the complete resonator,
2. a flaring section, nearly as long as the neck, where the diameter increases greatly,
3. a tapering section, which is open at the top.

Figure 6b shows the setup of the transfer function measurement of the pipe resonator. The simulation arrangement and the waveforms at the first four eigenfrequencies of the Vox humana resonator are displayed in Figure 7a and b, consequently. The comparison of the measured transfer function and the calculated input admittance function using analytical and FEM impedance models of a Vox humana pipe are shown in Figure 8. As seen, by applying the FEM for the simulation of the radiation impedance, the model is optimized and the calculated eigenfrequencies match the measured frequencies well.

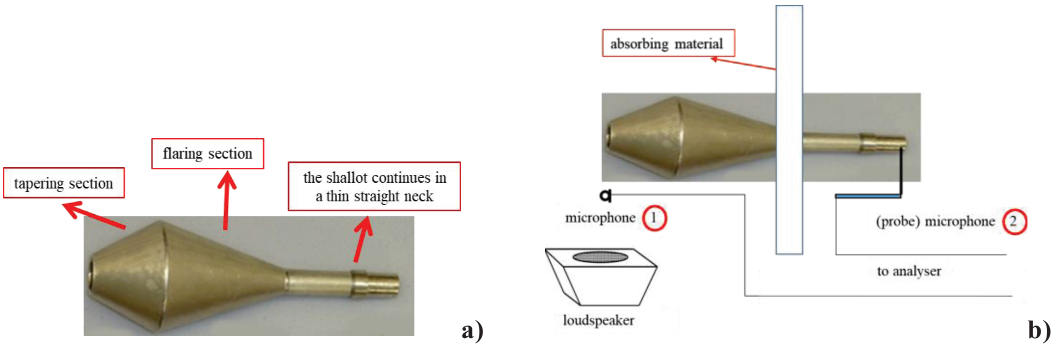


Figure 6. **a)** The resonator of a Vox humana pipe **b)** Measurement of the transfer function: the pipe resonator was excited by a loudspeaker with a sweep signal. Microphone 1 is at the end of resonator against the loudspeaker, (probe) microphone 2 is in the neck [18]

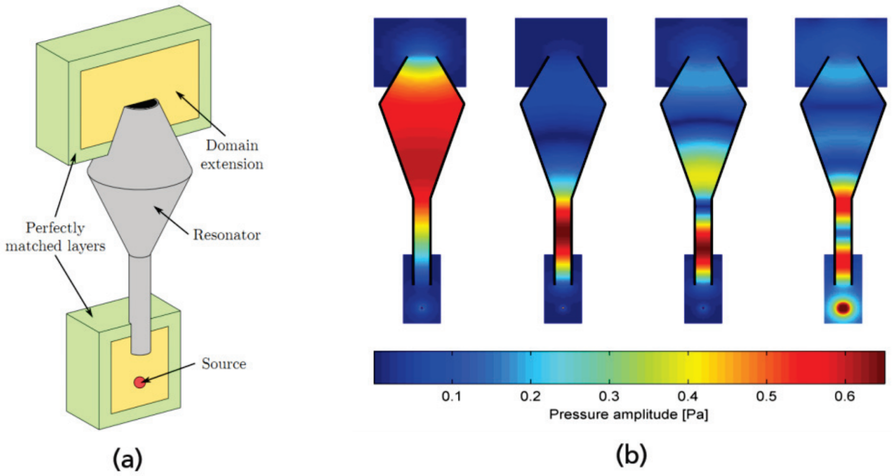


Figure 7. Simulation arrangement **(a)** and the first four eigenmodes **(b)** of the Vox humana resonator

Based on the measurement and simulation results a software tool has been developed for the design of reed pipes. In the following it is demonstrated how organ builders can use this method for dimensioning reed pipes. The main window of the software and the most important controls are shown in Figure 9. The resonator can be constructed individually as shown in the figure. In our example Figure 10a shows that by using the original resonator dimensions the strongest partial is not the third, which would be desired. By changing the resonator dimensions (the conical part near to the open end has been elongated) the frequency of the 1st natural resonance is tuned to the 3rd partial of the sound (Figure 10b).

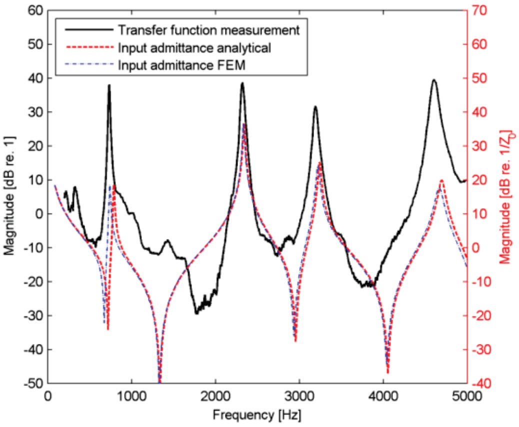
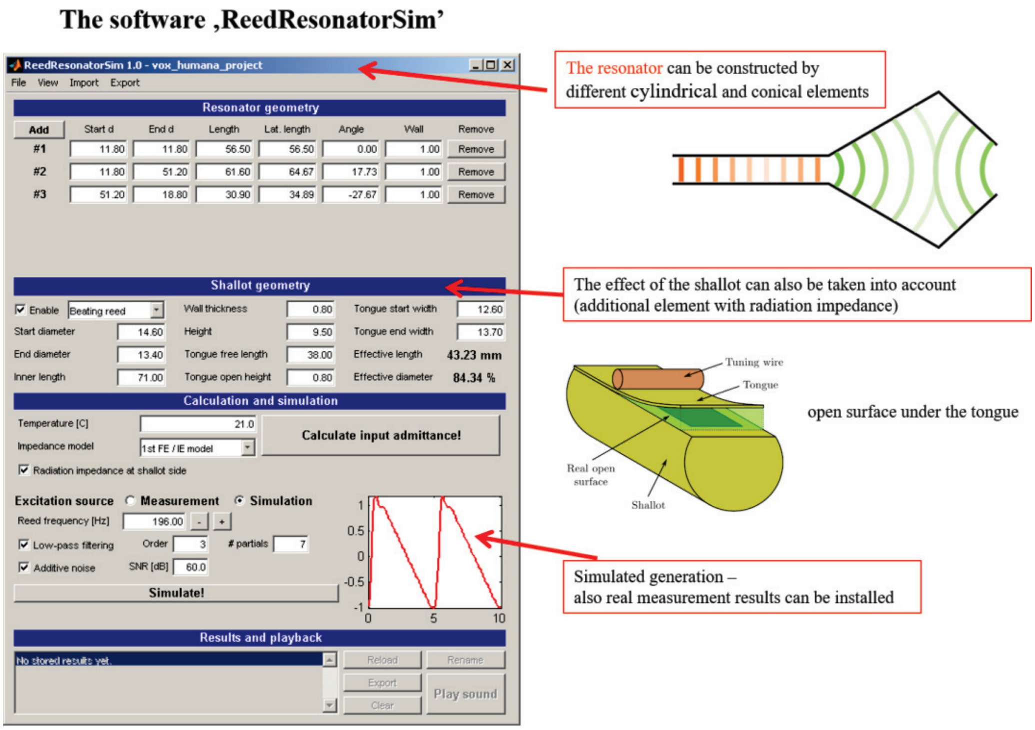


Figure 8. The measured transfer function and the calculated input admittance of a Vox humana resonator


The software ‚ReedResonatorSim'

ReedResonatorSim 1.0 - vox_humana_project

Resonator geometry

Add	Start d	End d	Length	Lat. length	Angle	Wall	Remove
#1	11.80	11.80	56.50	56.50	0.00	1.00	Remove
#2	11.80	51.20	61.60	64.67	17.73	1.00	Remove
#3	51.20	18.80	30.90	34.89	-27.67	1.00	Remove

Shallot geometry

☑ Enable: Beating reed
Start diameter: 14.60
End diameter: 13.40
Inner length: 71.00
Wall thickness: 0.80
Height: 9.50
Tongue free length: 38.00
Tongue open height: 0.80
Tongue start width: 12.60
Tongue end width: 13.70
Effective length: 43.23 mm
Effective diameter: 84.34 %

Calculation and simulation

Temperature [C]: 21.0
Impedance model: 1st FE / IE model
☑ Radiation impedance at shallot side

Excitation source ○ Measurement ● Simulation
Reed frequency [Hz]: 196.00
☑ Low-pass filtering Order: 3 # partials: 7
☑ Additive noise SNR [dB]: 60.0

Results and playback

No stored results yet.

The resonator can be constructed by different cylindrical and conical elements

The effect of the shallot can also be taken into account (additional element with radiation impedance)

open surface under the tongue

Simulated generation – also real measurement results can be installed

Figure 9. The main window of the software tool and the most important controls. The function shows the simulated excitation, which was adjusted on the basis of laser vibrometer and probe microphone measurements to make them as realistic as possible [18].

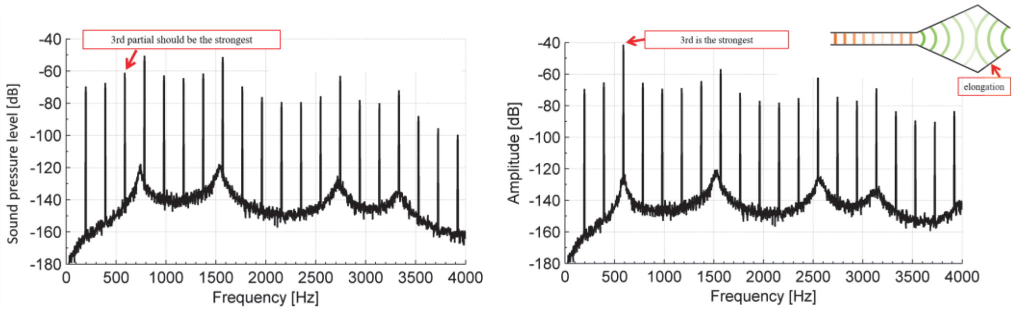


Figure 10. Simulation of the steady state sound spectrum of a Vox humana pipe **a)** with the original resonator dimensions **b)** with optimized resonator dimensions [18]

4 RESEARCH ORGAN AT THE FRAUNHOFER IBP

In the year 2011 a research pipe organ was built at the Fraunhofer IBP by the Werkstätte für Orgelbau Mühleisen, Leonberg for the scientists (Figure 11a). The pipe organ was financed by the state of Baden-Württemberg. Its transparent and unique scope of design allows the demonstration of research results, the investigation of technical and acoustical problems in organ building as well as the audible testing of ideas on organ sound. This organ contributes to further develop our knowledge on sound; it also allows new connections of art and science, of music and physics [19].

In this context it is now discussed why the research organ was necessary, which research results can be demonstrated, what are the specific characteristics of the research organ, and what significance does this instrument have for future research.

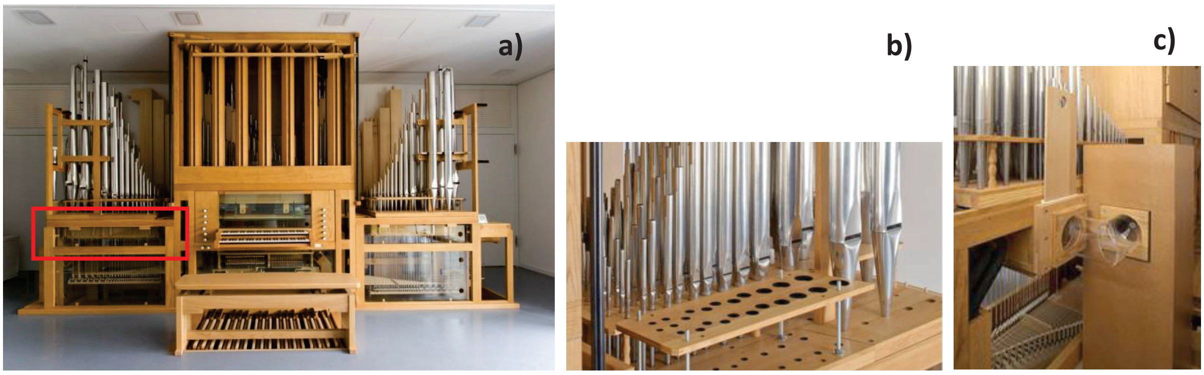


Figure 11: **a)** Research organ of the Fraunhofer IBP (built in 2011 by Werkstätte für Orgelbau Mühleisen, Leonberg). The red frame denotes the exchangeable wind chest. **b)** To test newly designed stops a blind slider is available with a pipe rack, which can be adjusted in height **c)** the outlet valve mounted as part of the innovative wind system.

4.1 Why a research organ?

The research organ serves as a demonstrator for numerous research results as well as it allows the investigation of problems on technology and sound directly at a real instrument. Moreover, it simplifies the dissemination of the knowledge in the field of organ research. In former times, new developments had to be tested at a church organ. It was difficult to obtain the permission for these measurements. In the majority of cases, first of all the instrument had to be modified by an organ builder. For example, several holes have to be drilled for the different detectors necessary for the measurements. Most measurements could only be carried out at night, since the ambient noise would have been too loud in the church during the day. These business trips always involved intricacies, as unexpected problems frequently occurred.

The details of the design of this pipe organ can only be partially described in this publication. They are gained from the results of many projects conducted by organ researchers at the IBP during the last 25 years [20]. The symbiosis of scientific and technological knowledge and instrument building broadens our knowledge of sound and creates new connections of physics and music, science and art.

4.2 Specific characteristics

- The pipe organ is transparent to the greatest possible extent to make visible and demonstrate the functioning of the mechanics.
- One wind chest of a division can be exchanged to allow the testing of new wind chests, valve constructions as well as pipe layouts (Figure 11a).
- The keyboard is prepared for the mounting contacts for electric controllable valves.
- The toe boards can be exchanged for experiments.
- To test new stops a blind slider is available with a pipe rack, whose height can be adjusted (Figure 11b).
- There are some blind grooves to analyze the effect of the wind flow, of the resonances in the grooves as well as of different outlet holes on the pipe sound.
- Two different wind systems are available: a traditional one and an innovative design with outlet valve system (Figure 11c) [21, 22]. The system can be switched from the traditional to the innovative one.
- Blowers are controlled by a frequency converter for continuous adjustment of the wind pressure.
- Removable swell shutters, developed by the IBP, are mounted in the swell organ (see details in Section 4.3).
- To visualize the air jet motions of flue pipes a groove is equipped for CO_2 connection.
- The motion of a beating as well as a free reed can be visualized by means of a stroboscope installed.
- Special wind chests are used for experiments as well as demonstration. Especially, a transparent wind chest with tone valves is operable either manually or by keyboard. A wind chest with cone valves and with membrane valves is also available.
- Besides the demonstration of different valve systems investigations of different wind chests can be conducted. They can also be used for the demonstration of innovative pipes.
- The metal pedal pipes are made of organ metal (tin-lead alloy) on the left side and of zinc on the right side of the instrument. Thereby it can be directly tested whether an influence of the material on the pipe sound can be heard.

4.3 Examples of innovations applied in the research organ

Several results of the pipe organ research of the IBP are applied in the research organ. For example, the design method, the construction and the control mechanism of the outlet valves of the innovative new wind systems have been developed in the course of two subsequent EU research projects [21, 22]. The dimensions of large wooden pedal pipes, furthermore both the chimney and reed pipes have been designed and optimized by means of software developed at the Fraunhofer IBP (Figure 12a and b). The application of different materials (lead-tin alloy vs. zinc) for the metal pedal pipes is based on the results of an earlier research project commissioned by the Grillo-Werke Aktiengesellschaft [23, 24].

Besides the innovations gained from EU-supported research other innovations have also been applied. For example, innovative removable swell shutters developed in cooperation with the organ building company of Mühleisen in Leonberg are mounted in the swell organ allowing better sound radiation and higher dynamics of organ music. The traditional (a) and innovative (b) swell shutters are depicted in Figure 13. The swell organ front is removable, therefore other swell shutter constructions can also be tested [25].

This swell shutter construction has been developed earlier in the course of a bilateral cooperation between IBP and Mühleisen. Models of the traditional and innovative swell shutter constructions were investigated in the anechoic room of the IBP. A loudspeaker with pink noise served as a sound source. The directional sound radiation characteristics of the two constructions are represented at 2500 Hz in Figures 14a and b. The traditional swell shutters radiate the sound asymmetrically. The innovative swell shutters have an acoustically more favorable symmetrical sound radiation.

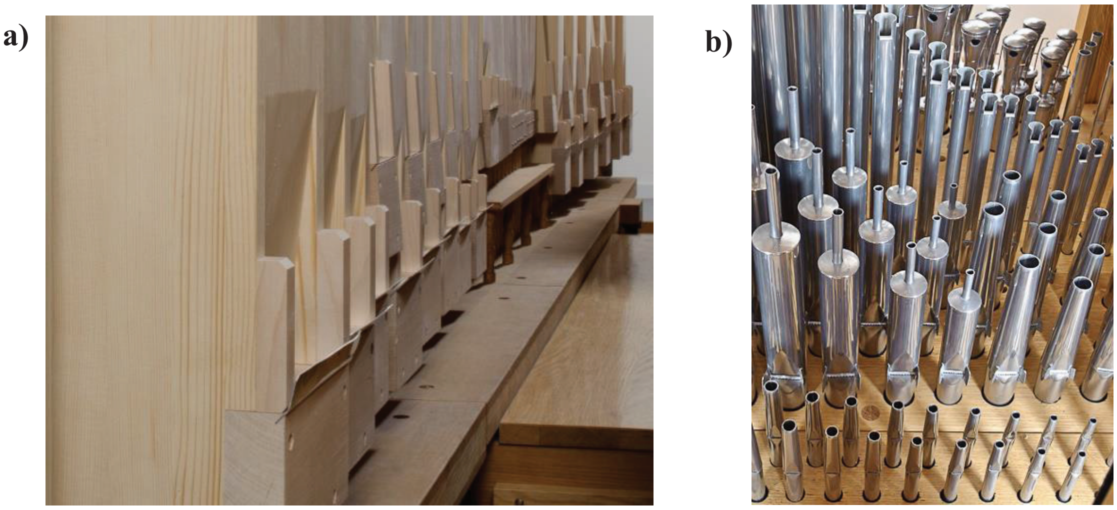


Figure 12: The dimensions and sound of wooden pipes **a)** and of chimney pipes **b)** have been optimized by means of software developed at the IBP.

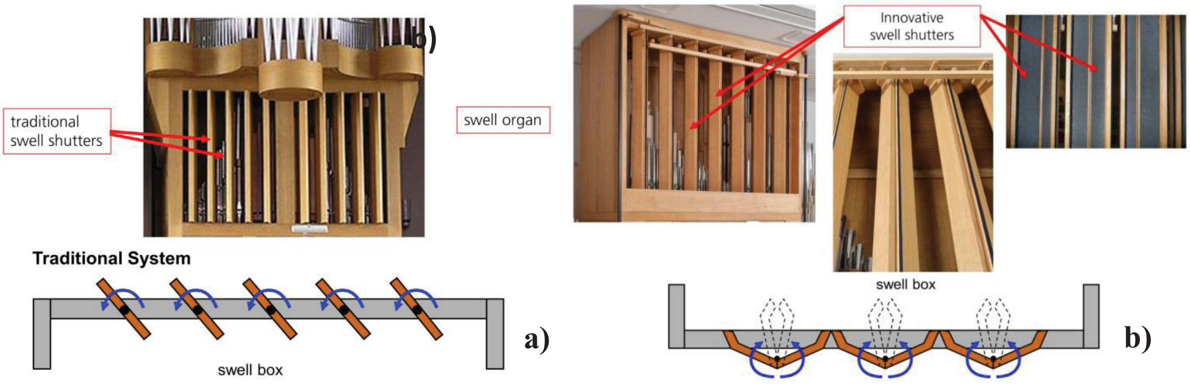


Figure 13: Traditional (a) and innovative (b) swell shutters. The innovative, removable swell shutters are mounted in the swell organ (b).

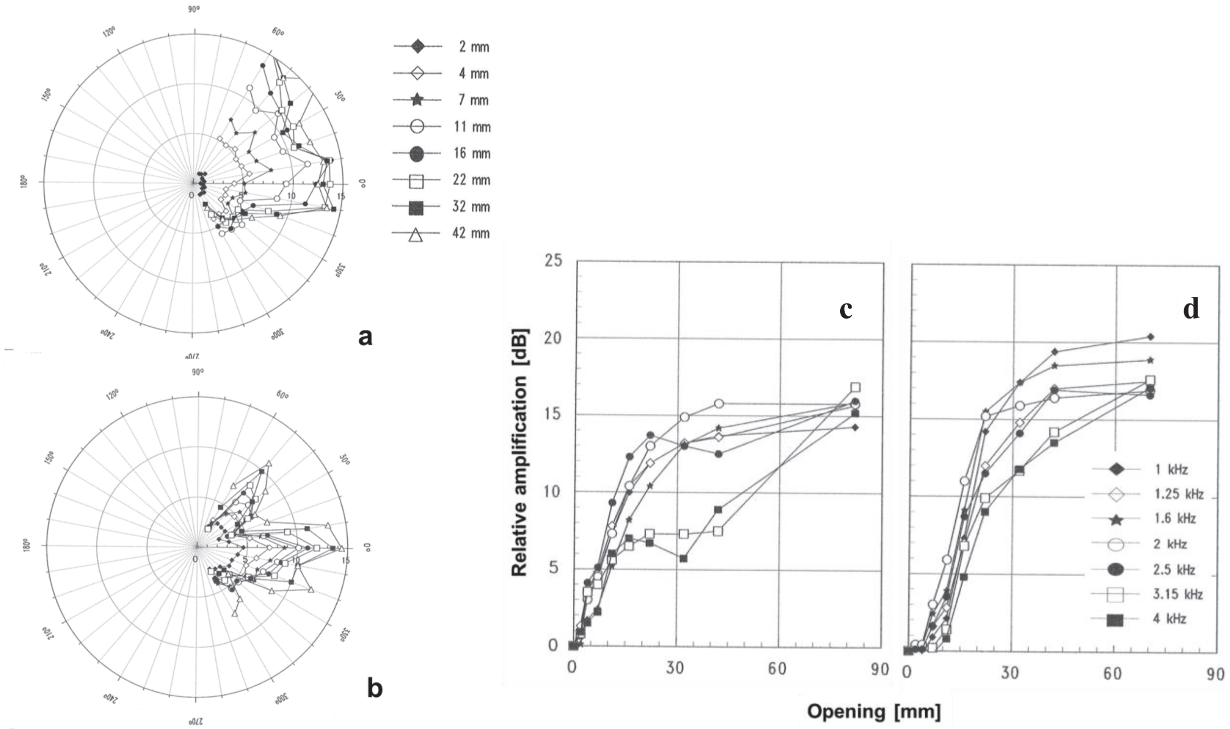


Figure 14: Directional sound radiation characteristics of the traditional (a) and innovative (b) swell shutters as a function of the opening at 2500 Hz. Sound amplification of the traditional (c) and innovative (d) swell shutters at 0 degree in different frequency ranges.

In Figure 14c the relative sound amplification referred to the closed situation of the traditional and innovative swell shutters at 0 degree in different frequency ranges is shown. The innovative construction (Figure 14d) achieves a significantly (by approx. 5 dB) higher relative sound amplification. In addition, the dynamics can be influenced in smaller steps (especially at the beginning of the opening) than with the traditional swell shutters.

5 DISSEMINATION OF RESEARCH RESULTS

The dissemination of research results is a very important task of the Fraunhofer IBP. The developed software and the results of the European research projects are primarily passed on to the organ building companies participating in the projects in form of project meetings and training. After a few years, however, the right to use these results is conferred by the partners and thus can be disseminated to other organ experts by intensive courses and workshops lasting several days. These events are being organized by using the research organ. Organ concerts are performed as well as concerts with organ and other musical instruments accompanied by generally understandable explanations of the physics of the presented musical instruments.

6 SUMMARY AND OUTLOOK

It has been shown, how the knowledge of the acoustics of the pipe organ is being adopted in applied research for supporting organ builders. Computer simulation optimized and verified by comparison with measurement results can be used for supporting organ builder companies in dimensioning the pipes. Software for optimizing the wind system (here not shown) and pipe organ sounds have been developed.

It was mentioned that by realizing applied research projects the applicable results are owned by the enterprises and so they should not be published for several years after finishing the work. For this reason the authors of the present paper plan to summarize the most important outcomes of earlier confidential European projects in a book. Nevertheless, as soon as possible the dissemination of knowledge has been carried out in the form of workshops organized for organ builder enterprises. These workshops have been the only possibility internationally for organ builders to learn about the acoustics of the organ and getting instructed for the application of research results, design methods, and software.

Furthermore, the extensive knowledge attained on the sound generation of organ pipes can serve as a guideline in improving the physical models of sound generation of flue and reed wind instruments.

At last but not least, our research organ will hopefully have the effect of creating new combinations of physics and music, science and art for the benefit and delight of people.

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