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Innovative methods for the sound design of organ pipes

Ph.D. Thesis Booklet

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1 Introduction

1.1 About pipe organ research in nutshell

Pipe organ research supplies traditional craftsmanship by novel measurement, theoretical and simulation techniques. Despite the fact that pipe organs have already been built for several hundreds of years, and that organ building is quite a traditional art, organ builders are still seeking ways to improve the quality of their instruments.

Traditionally, organ building is a hand manufacturing process, which means that pipes are assembled, tuned and voiced by handwork. Organ research does not aim to replace the work of organ builders and voicers, rather to increase the efficiency of the planning, building and voicing processes. This aim is achieved by means of the development of novel—often computer aided—design methods and technologies based on scientific background.

Novel industrial and artistic requirements also force the organ building community to apply new techniques in pipe design. One of the recent industrial challanges is the prohibition of the usage of lead—one of the essential pipe materials—inside the European Union. From the artistic point of view, a new requirement for the organ sound is the need of reproducing sounds of exotic (African or Asian) musical instruments. Both issues procure the need for new materials and pipe constructions.

From the physical point of view, the sound generation mechanism of organ pipes—either *labial* or *lingual*—is a complex process involving acoustical, mechanical and fluid dynamical phenomena inherently and non-linearly coupled. The complexity of the process explains the fact that the sound generation of wind instruments is still an active field of research in musical, aero- and numerical acoustics, and even in fluid dynamics. From the 19th century, a great number of relating scientific contributions have been published, including theory, measurement and simulation results.

1.2 Motivation and background

Discussions with a number of organ builders revealed that a lot of design rules in organ building practice lack scientific background. Traditional scaling rules of thumb are sufficient usually; however, in case of certain design problems no generally accepted methods exist.

The motivation of the research reported in this thesis is twofold. On the one hand it seeks solutions for specific issues in organ pipe scaling, proposing novel design methods in order to attain extended control over the sound characteristics and better perceived sound quality. On the other hand the thesis aims to provide scientific background for the aforementioned issues leading to more detailed physical models and a better understanding of the sound generation mechanism. Both objectives are approached by means of analytical and numerical modeling and validation by comparison to measurement results.

The industrial background of this thesis is covered by the European Projects INNOSOUND and REEDDESIGN. Beside the financial support provided by the European Commission, these projects have given an invaluable forum for discussions with the leaders of the European organ building community.

2 State of the art and literature review

2.1 General approach

Wind instruments (or *aerophones*) produce sound by means of pressure oscillations of an air column inside the body of the instrument, also called the *resonator*. In order to achieve steady state sound generation, the forced pressure oscillations must be maintained by means of the excitation mechanism. The excitation is realized in various manners in different families of wind instruments.[1] In case of labial organ pipes, sound is produced by means of an aeroacoustic excitation, whereas lingual pipes produce sound by means of vibrating metal tongue, often referred to as “reed”. The role of the resonator is similar in all cases: it provides acoustic feedback for the excitation mechanism and hence the resulting pitch is determined by the synchronization of these two oscillating systems.[2] Due to the synchronization effect, the generated sound is a periodic signal in the steady state, provided that the excitation is steady.

A general approach for modeling wind instruments is the separation of the system into two parts: the excitation is usually represented by a

[1]S. Adachi. “Principles of sound production in wind instruments.” In: *Acoustical Science and Technology* 25.6 (2004), pp. 400–405.

[2]M. Abel, S. Bergweiler, R. Gerhard-Multhaupt. “Synchronization of organ pipes: experimental observations and modeling.” In: *Journal of the Acoustical Society of America* 119.4 (2006), pp. 2467–2475.

nonlinear circuit, whereas the resonator is generally treated as a linear system. The latter is a reasonable approximation since the resonator operates at amplitudes of the linear acoustic regime. This approach has already been utilized successfully by Fletcher[3] and has been extended by Verge *et al.*[4]

2.2 Modeling the resonator

Besides having a crucial role in determining the pitch of flue pipes, the resonator also has a great influence on the timbre. These impacts are determined mostly by the geometry (length, diameter, size and shape of openings etc.) of the pipe body. In organ building the term *scaling* refers to the design phase of calculating the dimensions of each pipe in the organ. Although this procedure is performed following artistic requirements, the scientific methodology for the characterization of resonators is summarized in the sequel.

Generally, organ pipes can have various shapes and designs, however, in most cases the resonators are oblong and axisymmetric. The musically relevant frequency range of operation is under the *cutoff frequency* of the resonator, where only longitudinal modes propagate in the air column.[5] This limitation means a great simplification of the acoustic model, since the resonator can be represented as a one-dimensional system. The acoustic waveguide model of the resonator of an organ pipe consists of distributed and lumped parameter elements analogous to the representation of transmission lines applied in electromagnetics.

The one-dimensional model is used in order to attain the acoustic *input admittance* or *input impedance* function of the resonator. The input admittance function describes the behavior of the resonator in the frequency domain; however, by means of inverse Fourier transform it can also be applied for the time domain simulation of wind instruments.[6]

[3] N. H. Fletcher. "Sound production by organ flue pipes." In: *Journal of the Acoustical Society of America* 60 (1976), pp. 1119–1132.

[4] M. P. Verge, A. Hirschberg, R. Caussé. "Sound production in recorderlike instruments. II. A simulation model." In: *Journal of the Acoustical Society of America* 101.5 (1997), pp. 2925–2939.

[5] A. Miklós, J. Angster. "Properties of the sound of flue organ pipes." In: *Acustica-Acta Acustica* 86.4 (2000), pp. 611–622.

[6] S. Adachi, M. Sato. "Time-domain simulation of sound production in the brass instrument." In: *Journal of the Acoustical Society of America* 97.6 (1995), pp. 3850–3861.

The input admittance function was used previously by different authors for the characterization of various wind instruments. Caussé *et al.*[7] have successfully applied the model for the simulation of brass instruments. Kokkelmans *et al.*[8] have utilized the admittance model for the examination of the acoustic behavior of *chimney pipes*. The latter authors have also proposed the usage of the input admittance function for determining the optimal dimensions of the chimney; however, they have not published an optimization algorithm. The specific problem of sound design and optimization of chimney pipes is addressed later in Section 4.

From the input admittance function the eigenfrequencies of the acoustic resonator can be calculated. In case of labial organ pipes, the resonator is an acoustically open system and its natural frequencies are found at maxima of the input admittance.[9] Eigenfrequencies play a key role not only in determining the pitch but also in forming the timbre of the pipe sound. The latter is due to the fact that eigenfrequencies overlapping with harmonic partials can reinforce the given partials to a great extent.

Organ pipes transmit most of the sound power to the listener by means of sound radiation from the openings. A much lesser part of sound energy is transmitted through wall vibrations, yet this phenomenon is only relevant in special cases and very thin pipe walls.[10] Sound radiation from the openings can be described as non-perfect impedance terminations of the acoustic transmission line representing the resonator. In the low frequency regime these termination impedances can be interpreted as *length corrections*.[11] The shape of the openings can have a remarkable effect on the radiated sound spectra,[12] thus, the proper characterization of the openings is crucial with respect to the accuracy of the model.

The *radiation impedance* of an opening with arbitrary shape can not be computed analytically. However, in case of an unflanged cylindrical

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[7] R. Caussé, J. Kergomard, X. Lurton. "Input impedance of brass instruments – Comparison between experiment and numerical models." In: *Journal of the Acoustical Society of America* 75.1 (1984), pp. 241–254.

[8] S. J. J. M. F. Kokkelmans, M.-P. Verge, A. Hirschberg, A. P. J. Wijnands, R. L. M. Schoffelen. "Acoustic Behavior of Chimney Pipes." In: *Journal of the Acoustical Society of America* 105 (1999), pp. 546–551.

[9] P. M. Morse. *Vibration and sound*. Second edition. McGraw-Hill, 1948.

[10] C. J. Nederveen, J.-P. Dalmont. "Pitch and level changes in organ pipes due to wall resonances." In: *Journal of Sound and Vibration* 271 (2004), pp. 227–239.

[11] N. H. Fletcher, T. D. Rossing. *The physics of musical instruments*. Springer, 1991.

[12] A. Miklós, J. Angster. "Sound radiation of open labial organ pipes; the effect of the size of the openeings on the formant structure." In: *Proceedings of the International Symposium on Musical Acoustics*. Washington, 1998, pp. 267–272.

pipe, analytical treatment is possible, as shown by Levine & Schwinger.[13] Ingerslev & Frobenius[14] have proposed an approximation for the calculation of the length correction represented by the *mouth* opening of a labial organ pipe. Nevertheless, in case of an irregularly shaped opening, the analytical approach has to be dispensed with, and numerical treatment becomes inevitable.[15]

Tuning devices are often applied in organ pipe design in order to make the pipes easily retunable. In case of labial organ pipes one of the most often applied tuning devices is the *tuning slot*. The tuning slot is a symmetric discontinuity of the pipe body, resembling the arrangement of *toneholes* of woodwind instruments. Characterization of tonehole configurations has already been discussed in a number of contributions; the most recent formulation known to the author was published by Dalmont *et al.*[16]

A novel approach for the treatment of irregularities in the waveguide model is to compute the complete acoustic field near the irregularity using a 3D numerical model, and substitute the discontinuity in the 1D model by an *equivalent circuit* with parameters derived from the postprocessed field variables. This technique was proposed for the characterization of woodwind toneholes by Lefebvre & Scavone.[17,18]

Due to geometrical dissimilarities between woodwind toneholes and tuning slots, the tonehole models have a strongly limited applicability for modeling tuning slots. Furthermore, the tuning slot also affects the timbre and the observed sound quality of the pipe, which effects have remained undocumented in the scientific literature so far. The topic of tuning slot modeling is discussed in details in Section 4.

[13] H. Levine, J. Schwinger. "On the radiation of sound from an unflanged circular pipe." In: *Physical Review* 73.4 (1948), pp. 383–406.

[14] F. Ingerslev, W. Frobenius. "Some measurements of the end-corrections and acoustic spectra of cylindrical open flue organ pipes." In: *Transactions of the Danish Academy of Technical Sciences* 1.3 (1947), pp. 1–42.

[15] J.-P. Dalmont, C. J. Nederveen, N. Joly. "Radiation impedance of tubes with different flanges: numerical and experimental investigations." In: *Journal of Sound and Vibration* 244.3 (2001), pp. 505–534.

[16] J.-P. Dalmont, C. J. Nederveen, S. Dubos, V. Méserette, E. Sligte. "Experimental determination of the equivalent circuit of an open side hole: linear and non linear behaviour." In: *Acustica-Acta Acustica* 88.4 (2002), pp. 567–575.

[17] A. Lefebvre, G. P. Scavone. "Refinements to the model of a single woodwind instrument tonehole." In: *Proceedings of 20th International Symposium on Music Acoustics (Associated Meeting of the International Congress on Acoustics)*. Sydney and Katoomba, Australia, Aug. 2010.

[18] A. Lefebvre, G. P. Scavone. "Characterization of woodwind instrument toneholes with the finite element method." In: *Journal of the Acoustical Society of America* 131.4 (2012), pp. 3153–3163.

In case of lingual pipes, the role of the resonator and its interaction with the excitation mechanism are remarkably different than in case of labial pipes, as discussed by Miklós *et al.*[19] The strength of the coupling between the resonator and the excitation varies in a great range for different *stops*. In case of weaker coupling, the resonator simply acts as a filter characterized by its input impedance function. In case of reed pipes, the input impedance usually incorporates the radiation impedance of an open conical pipe end, which—to the best knowledge of the author—can not be calculated analytically. This issue is also addressed in Section 4.

2.3 Modeling the excitation

In organ building practice, the process of fine-tuning the excitation properties is referred to as *voicing*. Organ voicers setup the pipes one by one in subsequent adjustment steps. The reason of doing so is the fact that the excitation plays a key role in forming the speech, timbre and the *attack* of the pipe sound. As the proper representation of the excitation is of key importance in the model, techniques for its simulation are reviewed briefly in the following.

The *edge tone* excitation mechanism of labial organ pipes has already been examined by a number of researchers. Relations of flow parameters and frequencies of edge tone *stages* has been investigated by Holger *et al.*[20] Verge *et al.*[21] have examined and modeled the air jet and edge tone behavior in the attack transient of a labial organ pipe. Recently, Yoshikawa *et al.*[22] have published a jet–vortex-layer formation model of the sound generation and validated their model by experimental results.

As far as experimental work is concerned, the most recent results known to the author were achieved by Außerlechner *et al.*[23] The latter

[19] A. Miklós, J. Angster, S. Pitsch, T. D. Rossing. "Interaction of reed and resonator by sound generation in a reed organ pipe." In: *Journal of the Acoustical Society of America* 119.5 (2006), pp. 3121–3129.

[20] D. K. Holger, T. A. Wilson, G. S. Beavers. "Fluid mechanics of the edge tone." In: *Journal of the Acoustical Society of America* 62.5 (1977), pp. 1116–1128.

[21] M. P. Verge, B. Fabre, W. E. A. Mahu, A. Hirschberg, R. R. Hassel, A. P. J. Wijnands, J. J. Vries, C. J. Hogendoorn. "Jet formation and jet velocity fluctuations in a flue organ pipe." In: *Journal of the Acoustical Society of America* 95.2 (1994), pp. 1119–1132.

[22] S. Yoshikawa, H. Tashiro, Y. Sakamoto. "Experimental examination of vortex-sound generation in an organ pipe: A proposal of jet vortex-layer formation model." In: *Journal of Sound and Vibration* 331 (2012), pp. 2558–2577.

[23] H. Außerlechner, T. Trommer, J. Angster, A. Miklós. "Experimental jet velocity and edge tone investigations on a foot model of an organ pipe." In: *Journal of the Acoustical*

authors have published reproducible velocity profile and edge tone measurements performed on a high-precision pipe foot model.

With the increased computational capacity available at hand, computer simulation of the sound generation mechanism has become feasible. Kühnelt[24] reported the 3D flow simulation of a simplified pipe model. More recently, Fischer & Abel[25] presented compressible 2D *large eddy simulation* of the air jet and pressure oscillations of a *stopped* labial pipe.

Recently, Vaik & Paál[26] published simulation results of the free jet and edge tone generation in a 2D numerical flow model set up based on the aforementioned model of Außerlechner *et al.* They have reported good agreement of measurement and simulation results attained using various turbulence modeling techniques. However, due to the limitations of the 2D model, 3D effects of the flow are omitted in their model. The effects of extending the flow and edge tone simulations into 3D are discussed later in Section 4.

The excitation mechanism of lingual organ pipes is discussed much less in the corresponding literature. Miklós *et al.*[27] have compared plucked and blown reed vibrations and proposed an oscillation model taking aerodynamic and acoustic forces acting on the reed into account. However, their model has not been verified quantitatively due to the difficulty of the experimental determination of various parameters used in the model.

To the best knowledge of the author no numerical simulation results were published on the sound generation mechanism of reed pipes. The latter is indeed a complex problem, involving acoustical and fluid dynamical phenomena coupled to mechanical vibrations. Although the task would be very interesting and challenging at the same time, the development of such a simulation model is out of the scope of this thesis.

Society of America 126.2 (2009), pp. 878–886.

[24] H. Kühnelt. "Simulating the sound genereation in flutes and flue pipes with the Lattice-Boltzmann-Method." In: *Proceedings of the International Symposium on Musical Acoustics*. Nara, Japan, Mar. 2004, pp. 251–254.

[25] J. Fischer, M. Abel. "Synchronization of nonlinear, acoustical oscillators." In: *DAGA2012 38. Jahrestagung für Akustik*. Ed. by H. Hanselka. Deutsche Gesellschaft für Akustik e.V. (DEGA). Darmstadt, Germany, 2012, pp. 197–198.

[26] I. Vaik, G. Paál. "Flow simulations in an organ pipe foot model." In: *Journal of the Acoustical Society of America* 133.2 (2013), pp. 1102–1110.

[27] A. Miklós, J. Angster, S. Pitsch, T. D. Rossing. "Reed vibration in lingual organ pipes without the resonators." In: *Journal of the Acoustical Society of America* 113.2 (2003), pp. 1081–1091.

3 Methodology

This section briefly summarizes the methodology applied throughout the thesis. Without the need of explaining every detail, the most important aspects of the developed and utilized techniques are reviewed.

Following the general methodology presented in Section 2.1, the background of the techniques discussed in the thesis is the separation of the sound generation mechanism into a non-linear excitation and a linear acoustic resonator part.

Most of the resonator forms investigated in the thesis are axisymmetric. In these cases, the one-dimensional acoustic waveguide model of the resonators were applied in order to determine the input admittance function and the eigenfrequencies of the pipe.

The one-dimensional model was also applied for the optimization of resonator scaling, e.g. in case of chimney pipes. Development of scaling methods allowing sound design required the usage of heuristic and unconstrained global optimization methods, such as the Nelder – Mead technique.[28]

Modeling irregularities, like tuning slots or the radiation impedance from the open conical pipe end, involved the usage of different tecnhiques in numerical acoustics, such as finite or boundary element methods. In order to reduce the size of the computational model and increase the flexibility of the simulations, postprocessing procedures were applied for deriving equivalent parameters from the computationally evaluated acoustic fields. Hence, the resulting equivalent acoustic circuits could be inserted into different one-dimensional models.

Modeling the flow field and the edge tone in a labial pipe foot model required the numerical solution of the Navier – Stokes set of equations. Three-dimensional flow models with over a million degrees of freedom involved the usage of highly parallelized simulation runs performed on a supercomputer grid.

Validation of model results was an important step of the methodology applied throughout the thesis. Results attained either by analytical or numerical models were validated by means of measurements whenever it was possible. When the sound quality of certain pipe designs had to be assessed, comparative listening tests were performed with the help of experienced organ voicers.

[28] J. A. Nelder, R. Mead. “A simplex method for function minimalization.” In: *The Computer Journal* 7 (1965), pp. 308–313.

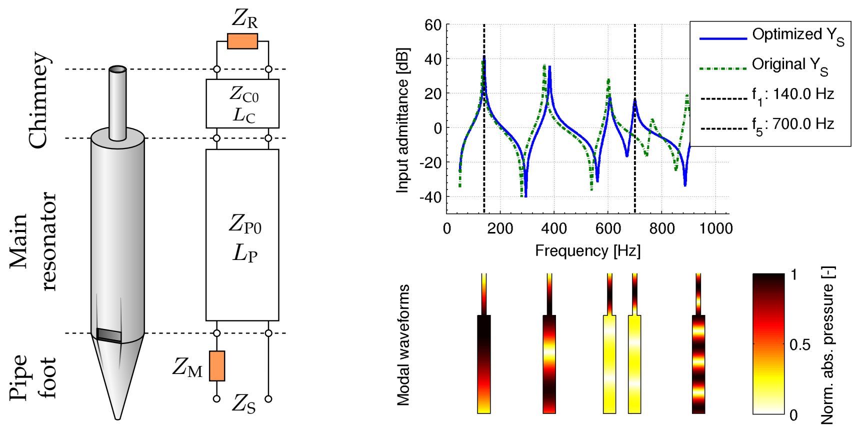


Figure 1. Chimney pipe model (left) and admittance optimization (right)

4 Results

This section briefly presents the most important results discussed in the thesis. The scientific achievements behind the results presented in this section are summarized as theses in Section 5, whereas the applications incorporating them are introduced in Section 6.

4.1 Sound design of chimney pipes

The schematic and the one-dimensional acoustic model of a chimney pipe is depicted in Figure 1. The pipe body consists of two main parts: (1) the main resonator and (2) the so called chimney. The chimney acts halfway between an open and a stopped termination of the main resonator.

The traditional aim of the chimney is to enhance some of the partials (the third or the fifth, typically) in the pipe sound, providing a special, bright character of sound. However, as it will be shown, current design methods fail to fulfill this requirement.

In order to achieve the most effective amplification of certain partials, optimized scaling techniques were proposed utilizing the unidimensional waveguide model of the pipe, depicted in Figure 1. The optimization methods provide the following functionality:

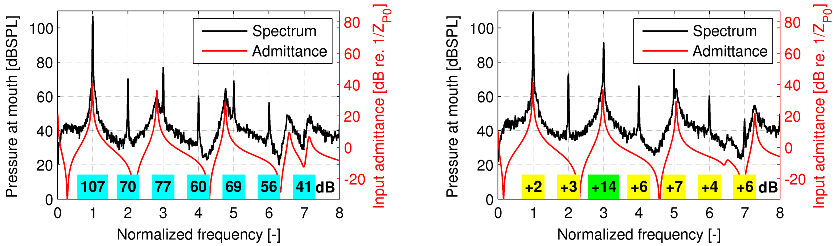


Figure 2. Chimney pipe optimization: original pipe (left), optimized pipe (right)

- The pitch of the pipe is adjusted by tuning the first eigenfrequency of the pipe, whereas the chosen partials are amplified by tuning other eigenfrequencies to overlap with them, as illustrated on the right hand side of Figure 1.
- The optimization methods can operate on different sets of design parameters. The fixed parameters and optimization targets can be selected arbitrarily.

The difficulty, that the dependence of the eigenfrequencies on the pipe dimensions is complex, is overcome by two optimization strategies.

1. A heuristic iterative approach was established for the special case when the length of the main resonator and that of the chimney are the optimization targets. With an approximative first guess on the chimney length the proposed algorithm provides fast convergence and very low computational cost at the same time.
2. When the number of optimization targets is higher, a cost-function-based approach utilizing the simplex technique is used. The global optimum is found by evaluating the input admittance function in every iteration, which requires significantly more computational effort than the heuristic approach.

The result of the optimization is depicted in Figure 2. As it can be seen, the 3rd partial is amplified greatly compared to the reference pipe using the proposed methods. The effectiveness and applicability of the proposed optimization procedures were validated by initial listening experiments performed by skilled organ voicers on chimney pipes built with optimized dimensions.

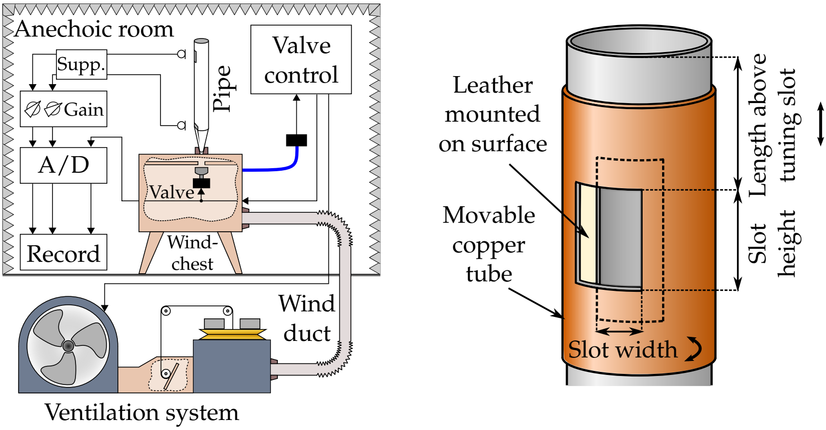


Figure 3. Sound spectrum measurement setup (left), adjustable tuning slot (right)

4.2 Tuning slot model

Tuning slots are tuning devices often used on narrow-scaled labial pipes, used e.g. in *Salizional* or *Gamba* stops. Besides changing the pitch of the pipe, the tuning slot also has a remarkable effect on the timbre. Discussions with organ builders revealed that there are no generally accepted methods for scaling tuning slots. The applied rules of thumb relate the dimensions of the slot with the pipe diameter only.

In order to accurately determine the impact of the slot geometry on the sound characteristics, reproducible measurements were performed on an experimental organ pipe with an adjustable tuning slot, as illustrated in Figure 3.

The measurements have proven that current design traditions do not provide sufficient control over the timbre. It was shown, that the eigenfrequency-structure of the resonator is affected by the slot to a great extent, and that the latter is closely related to the properties of the resulting sound. It was also found, that in order to exploit the capabilities of the slot, the geometry of the slot should be designed with respect to the desired timbre and should not depend solely on the pipe diameter.

To be able to foretell and quantitatively characterize the tendencies observed in the measurements, an accurate acoustic model of tuning slots needed to be constructed. Therefore, numerical models of tuning slots

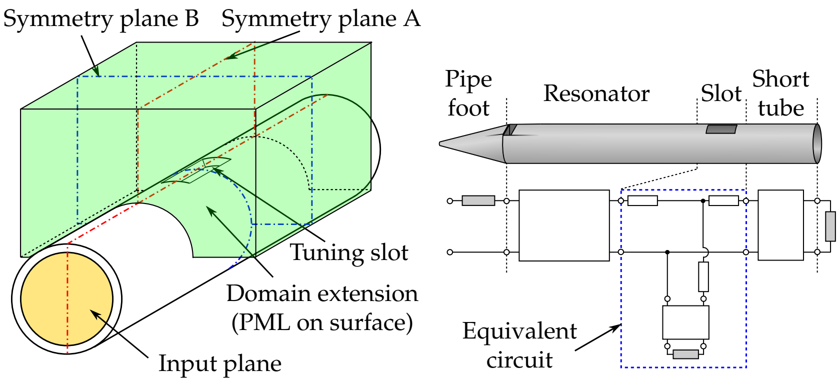


Figure 4. FE / PML tuning slot model (left) and its equivalent circuit (right)

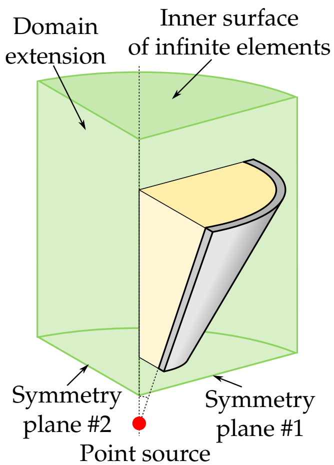
were created utilizing the finite element (FE) and *perfectly matched layer* (PML) techniques, as depicted in Figure 4. By means of computer simulation and subsequent postprocessing, the equivalent circuits representing the modeled tuning slots were obtained.

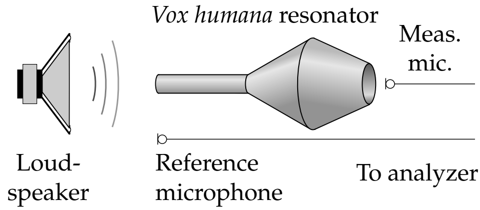
The calculated equivalent circuits can straightforwardly be applied in one-dimensional models, as shown on the right hand side of Figure 4. The resulting hybrid model provides flexibility and good computational performance. By means of comparison to measurement results, the proposed model was shown to provide more accurate results than similar tonehole models. The new model can also be utilized in the development of novel scaling methods allowing sound design of tuning slot pipes.

4.3 Acoustic model of reed pipe resonators

Resonators of lingual pipes of different stops are designed in various shapes. Nevertheless, the resonator shapes applied most often in practice are axisymmetric and consist of cylindrical and conical sections. In case of lingual pipes—especially for the kinds that operate with weak mechanical–acoustical coupling—the influence of the resonator on the timbre is much greater than that on the pitch.

In order to determine the effect of the resonator on the resulting character of sound, the transfer function (or input impedance function) of the resonator must be calculated. This involves the incorporation of the ra-





Mode	Meas. [Hz]	Ana. [Hz]	Err. [cent]	FE/IE [Hz]	Err. [cent]
1st	**735**	**788**	**120.5**	**748**	**25.7**
2nd	2 319	2 339	14.9	2 317	-1.5
3rd	3 192	3 239	25.3	3 212	10.8
4th	4 605	4 695	33.5	4 650	16.8
5th	5 425	5 566	44.4	5 502	24.4
6th	6 469	6 695	59.4	6 619	39.7

Figure 5. Radiation impedance model (left) and its application (right)

diation impedance from a conical pipe end. Since the latter can not be evaluated analytically, a numerical solution was proposed.

The model shown in Figure 5 is a finite – infinite element arrangement for the simulation of the radiation impedance of a conical pipe end. The computer simulations were performed on several different models, varying the opening angle of the cone. To be able to apply the simulation results directly in the one-dimensional model, the postprocessed radiation impedances were stored in a scalable database.

The impedance model was validated by means of comparison to transfer function and spectrum measurements. It was found that the radiation impedance has a great effect on the calculated input impedance, especially in the case of tapering pipe ends. It was shown that the proposed impedance model gives more accurate results in these cases, as illustrated by Figure 5.

4.4 Three-dimensional edge tone generation model

Two-dimensional free jet and edge tone CFD simulations have already been performed and published by other authors. Nevertheless, in order to assess the quality of the results provided by these models, it is worth comparing the 2D models to more complex, 3D models. Naturally, the extension of the simulation into three dimensions means a significant in-

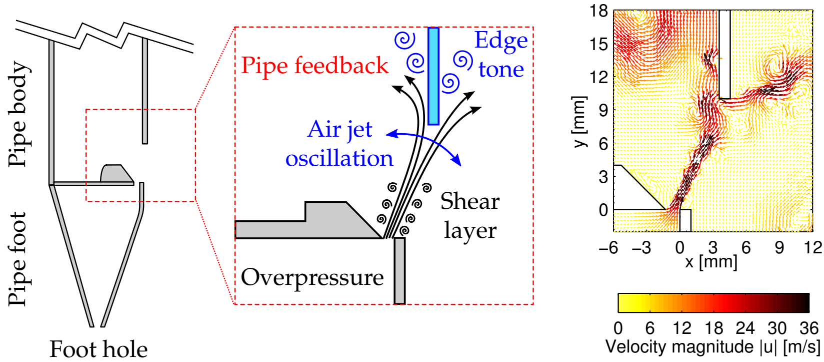


Figure 6. Pipe foot model (left) and edge tone simulation (right)

crease in the number of degrees of freedom, which requires more computational effort.

Figure 6 depicts the foot model of a labial organ pipe and the edge tone generation mechanism. This foot model has been used for the generation of 2D and 3D meshes. Solution of the 3D problems involved more than a million degrees of freedom and therefore the simulations were run on a supercomputer, using up to 48 processor cores simultaneously. The simulations were performed using laminar and large eddy turbulence models.

Two different simulation arrangements were created. In the "Jet" case the free jet setup was modeled, the upper lip being omitted from the model. In this case the velocity and turbulence profiles of the free jet were evaluated. In the "Edge" arrangement, the upper lip was inserted, and the spectra of the pressure forces acting on it were examined.

Comparison with flow and edge tone spectrum measurements have verified that the proposed 3D model is superior compared to the 2D models. In the "Jet" case, the model gives better estimation of velocity profiles, whereas in the "Edge" case it predicts the frequencies of the tonal components of the edge tone more accurately.

5 Theses

Thesis group I (Optimization of chimney pipe resonators)
I have introduced a novel methodology for the sound design of chimney pipes. Based on the one-dimensional acoustic model of the pipe, I have derived an optimization strategy for scaling the resonator. Contrary to traditional methods, the proposed technique provides control over the timbre of the pipe in the scaling phase. I have validated the applicability of the method by means of objective and subjective comparisons.

Thesis I.1
I have shown by means of theoretical and experimental examination that the current design rules of chimney pipe resonators are suboptimal, since they do not allow sound design in the scaling phase and leave certain capabilities of the resonator unexploited. [J2, C2, C3]

Thesis I.2
I have proposed a new methodology for the optimal design of chimney pipe resonators. I have suggested two optimization procedures for different sets of target parameters. The amplification of the chosen partials is achieved by tuning the eigenfrequencies of the resonator through the geometry parameters. I have verified the applicability of the proposed technique by means of laboratory measurements and subjective evaluation of the sound quality of experimental pipes built using the optimization procedure. [J2, C5, C6, C8]

Thesis group II (Tuning slot characterization and modeling)
I have performed a measurement campaign in order to accurately assess the impact of the tuning slot on the acoustic behavior of labial organ pipes. I have proven that current design rules for tuning slot pipes do not provide sufficient control over the character of the sound. I have developed a novel model for the characterization of tuning slots using finite element simulation. I have shown, that by using the proposed model, an optimal scaling method can be developed, overcoming the limitations of current design rules.

Thesis II.1
I have found that the steady state spectrum of labial organ pipes mounted with a tuning slot has a unique behavior. I have determined and documented the impact of scaling parameters on the sound characteristics by

means of reproducible measurements. I have proven that the observed tendencies are explained by the tuning slot's effect on the eigenfrequency-structure of the pipe. [J3, C4, C7]

Thesis II.2
I have shown by spectral analysis and subjective evaluation of recorded pipe sounds, that current design rules of thumb do not provide sufficient control over the timbre. I have recommended an alternative scaling approach, which revises the relation between the parameters of the slot and that of the pipe and can be utilized for the sound design of tuning slot pipes. [J3]

Thesis II.3
I have proposed a new formulation for the equivalent acoustic parameters of tuning slots based on the results of finite element simulations. I have verified that the novel technique gives a more accurate prediction of the eigenfrequencies than traditional woodwind tonehole models applied to tuning slots of labial organ pipes. [J4, C5–C7]

Thesis group III (Development of modeling methodology)
I have achieved novel results regarding the simulation of acoustic and fluid flow phenomena in labial and lingual organ pipes by the combined usage of the one-dimensional waveguide, the three-dimensional finite and infinite element, and finite volume techniques.

Thesis III.1 (Modeling resonators of reed organ pipes)
I have introduced a methodology that combines a one-dimensional acoustical model with three-dimensional finite – infinite element simulation of the radiation impedance. I have shown that by means of post-processing the simulation results, the method can adaptively be applied in the acoustical waveguide type simulation of axisymmetric resonators. I have also proven that the proposed technique gives better prediction of the eigenfrequencies than traditional methods, without additional computational effort. [C11, C15]

Thesis III.2 (3D simulation of edge tone generation)
I have extended previous two-dimensional CFD models of the air jet and edge tone generation into three dimensions. I have shown that this extension, which is claimed to be indifferent by other authors, has a significant impact on the simulation results. I have also shown that the proposed

three-dimensional model provides a better fit to measured data regarding both free jet and edge tone simulations. [C13]

6 Applications

6.1 Software developed for organ builders

In the frame of the European projects `INNOSOUND` and `REEDDESIGN`, the results presented in Sections 4 and 5 were applied directly in the implementation of various pieces of software. These standalone tools provide user interface for applying the techniques introduced above in the practice of designing organ pipes. These software codes and the incorporated results of this thesis are briefly introduced below.

`SoundAnalysis`[29] is a software tool for the analysis of organ sound. The implementation contains signal processing algorithms that were developed to fit to the specific properties of organ sound, such as the analysis of attack and decay transients, envelope detection etc.

`INNOScale`[30] is a complex design program, which implements traditional and innovative scaling methods for whole organ stops and divisions. The code contains novel techniques, such as optimal design of narrow wooden pipes or chimney pipe scaling; the latter presented in Section 4.1.

`ReedResonatorSim`[31] is a simulation tool for the resonators of lingual pipes. This piece of software facilitates the design of axysimmetric resonators and shallots and provides an interface for the direct comparison of predictions and measurements. The code incorporates the model and results presented in Section 4.3.

6.2 **`MATLAB`** toolbox contribution

Development of the modeling methodology also lead to the incorporation of the coupled FE/BE, Infinite Element, Perfectly Matched Layer techniques and other supplementary algorithms into an in-house BEM/FEM

[29] © A. Miklós, S. Pitsch, P. Rucz, T. Trommer, 2010–2013.
[30] © J. Kirschmann, A. Miklós, S. Pitsch, P. Rucz, 2010–2012.
[31] © P. Rucz, 2013.

toolbox, called `NiHu`. The toolbox mainly serves research and educational purposes, however, it is also capable of handling problems of industrial size.

In the last four years eight—bachelor's and master's—theses from the students of the Laboratory of Acoustics and Studio Technologies have applied and contributed to the techniques implemented inside the toolbox. The toolbox was published in the publilications [J5, C9, C12, C14].

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