

Executive summary:

Innovative Methods and Tools for the Sound Design of Organ Pipes

The main objective has been to solve practical problems concerning the voicing of labial organ pipes, and to develop innovative methods and tools for helping the voicing adjustments and sound design work of organ builder small and medium-sized enterprises (SME)s. The degree of dissemination to countries with different technical and cultural tradition of organ building has been large.

A better scientific understanding of the voicing steps on the attack and the timbre of labial organ pipes has been necessary to develop innovative tools for helping the work of the voicers though a scientific model of the voicing adjustments which have not been available yet. This goal has been achieved by scientific investigations of the effects of the voicing steps on the pipe sound by laboratory experiments and scientific analyses. The main objectives have been as follows:

- Better sound quality of labial pipe ranks of pipe organs with optimization of the voicing methods and steps,
- Reduced costs of voicing adjustments by a scientifically based optimizing of the voicing procedure,
- Reduced costs of pipe manufacturing through innovative methods and tools: user friendly design software based on a scientific sound design method.

These objectives have been achieved by targeted research carried out by the RTD partners of the project. The SME partners contribute to the project by designing the pipes for the investigations, by providing organ pipes and voicers for the laboratory experiments, by evaluating the results in their workshops. A considerable cost reduction and a better quality of the sound of the pipe organs could be expected.

Project Context and Objectives:

Innovative Methods and Tools for the Sound Design of Organ Pipes

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Examples of the work performed since the beginning of the project:

Development of optimal scaling of the depth and width of wooden pipes

In case of wooden pipes the reduction of pipe width would be desirable, because the space requirement of the pipe organ could then also be reduced. On the other hand, the sound quality could be worse for too narrow pipes. The aim is to find the narrowest scaling of wooden pipes with still appropriate sound quality.

Laboratory experiments

Optimal scaling of the depth and width of wooden pipes has been developed in order to help the design of the instrument to the space requirements of the room. A series of differently scaled wooden pipes has been acoustically investigated in the anechoic room of the IBP.

On the basis of the results a design and scaling method have been developed that can take into account the effect of wall dimensions on the stationary spectrum of the sound.

Computer simulation of wooden pipe forms

The eigenfrequencies of the pipe resonator have been numerically simulated by means of the Finite Element Method and/or of the Boundary Element Method (Figs 3-4). The influence of the depth and width of wooden pipes on the formant structure of the stationary sound has been investigated and optimized.

Design software for optimal scaling of wooden pipes

On the basis of the elaborated method design software for the optimal scaling of the depth and width of wooden pipes has been developed. With the help of the software the organ builder can optimize the dimensions of the wooden pipes with the aim to reduce the length and so the price of the wind chest, but maintaining an optimal sound quality in the same time.

Practical solution for tuning with a tuning slot

Pipes equipped with a tuning slot (Expression) have a specific timbre, which are clearly distinguishable from the timbre of clearly cut pipes or pipes having a tuning roll. The size and position of the tuning slot influences the formant structure of the sound spectrum radiated at the open end of the pipe. However, the tuning slot is also used for adjusting the pitch of the pipe. Therefore the pipe cannot be tuned without changing the sound character. Aim of this Subtask was to be able to influence the formant structure of the sound spectrum according to the imagination and wish of the organ builder but to be able to tune then the pipe without changing the sound character.

On the other hand the character of the spectrum changes (8-9-10th partials) with the length of the tuning slot. These character changes should be avoided with a new kind of tuning arrangement which can be designed with an innovative software.

Development of optimal scaling of the chimney and the pipe resonator of chimney flutes

Optimal scaling and design of chimney flutes have been developed by means of appropriate laboratory experiments and computer simulations. Design software has also been developed for the optimal scaling of chimney flutes.

Stopped pipes produce mostly odd harmonics; the addition of a chimney adds more even harmonics to the sound. The length and diameter of the chimney varies considerably from builder to builder. The real effect of the chimney on the sound is not known and a method of sound design does not exist until now. Therefore, organ builders cannot utilize the possibilities of this complex pipe form. Because of this it is crucial to investigate the function of the chimney in the sound articulation of the pipe.

A series of differently scaled chimney pipes has been acoustically investigated in the anechoic room of the IBP. The measurement results, together with the results of computer simulations of the BME have been used for developing a design method of chimney pipes, which takes into account the properties of both acoustical systems and provides an optimal matching of them. New voicing and tuning methods have also been developed for the new chimney pipe constructions.

Design software for optimal scaling of flue organ pipes (IBP, BME)

On the basis of the elaborated theories according to the different tasks of the project design software has been developed to help the organ manufacturers finding the optimal scaling and voicing for various pipe types and save quite some time in the industrial process of organ builders.

SME (small and medium-sized enterprise)-Partners:

Werkstätte für Orgelbau Mühleisen GmbH, Leonberg, Germany

Société de Construction d'Orgues Muhleisen sarl, Strasbourg, France

Flentrop Orgelbouw B.V., Zaandam, The Netherlands

Orgelbau Schumacher GmbH, Baelen, Belgium

Blancafort, orgueners de Montserrat S. L., Collbato, Spain

Oficina e Escola de Organaria, LDA, Esmoriz (Porto), Portugal

Fagmilia Artigiana Fratelli Ruffatti S.n.c., Padova, Italy

Johannes Klais Orgelbau GmbH & Co. KG, Bonn, Germany

Organ Work Manufacture of Pécs, Pécs, Hungary

Orgelmakerij Boogaard, Rijssen, Niederlande

Partners for research and technological improvements:

Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.,

Institut für Bauphysik, Stuttgart, Germany

Steinbeis GmbH & Co. für Technologietransfer, Steinbeis Transfer Center for Applied Acoustics, Stuttgart, Germany

Budapest University of Technology and Economics, Budapest, Hungary

http://www2.ibp.fraunhofer.de/akustik/ma/index_e.html

Project Results:

WP 1 Voicing

Task 1.1: Analysis and development of different voicing and tuning methods by laboratory experiments

Different problems of the voicing and tuning practice will be analysed and optimized by laboratory experiments.

This task is divided into the following Sub-tasks:

Sub-task: 1.1.1: Analysis and development of the cut-up relation relative to the diameter or to the length of the pipe. (MühLe, IBP)

The effect of the cut-up on the stationary sound and attack transient of model pipes having identical shape and dimensions but different mouth heights will be investigated. The aim is to find optimal cut-up sizes through the whole compass of the stop instead of the traditional, quite rigid relation relative to the flue width.

At first pipe models have been manufactured by the organ builder SMEs to investigate the effect of the cut-up relation relative to the diameter or to the length of the pipe.

A pipe with an adjustable upper lip for an infinitely variable adjustment of the cut-up height of the pipe mouth was also available. The special characteristic of another pipe model is a variable resonator length.

Investigations on pipe models allowed the analysis of the influence of important parameters of the dimensioning of the pipes on the sound to be generated. The pipe with adjustable length showed unusual behaviour. Strong drops in the amplitudes of the partials occurred at a certain resonator length, and the sound became unstable. Moreover, clear shifting in the pitch during the attack transient was perceivable in this unstable range, which partly disappeared only after a few seconds to pass to the 'correct' fundamental frequency then. Synchronization of the oscillation of the air jet at the labium with the oscillation of the air column in the resonator was obviously not possible at any scaling without any disturbance.

The pipe with adjustable cut-up height allowed investigations in how far the sound design is changed by various cut-up heights. In the process, various harmonics of the pipe sound were achieved at different cut-up heights. In addition, the clear correlation between the frequencies of the mouth tone peaks and the cut-up height could be verified. These measurements deliver very valuable information about the physical behaviour of the sound of flue pipes as a dependency on the cut-up height.

Several flue pipes have been transported to the lab by the SME partners and several experiments have been carried out with different voicers.

More detailed scientific results are described in Deliverable 1.1: Manual: Voicing and Tuning in section 2.1.

Sub-task 1.1.2: Voicing at the languid or at the upper lip. (MuStra, IBP)

Attack transient and stationary sound can be effectively influenced by the direction of the air jet emerging from the flue. There are two traditional voicing methods for changing this direction; voicing at the languid and voicing at the upper lip. Modern organ building applies mostly the voicing at the languid, while some earlier traditions have preferred the voicing at the upper lip. These two voicing methods will be investigated and compared in this Sub-task, to understand the similarities and differences of both voicing methods and to determine, in which cases the voicing at the languid could be substituted by the simpler voicing at the upper lip. For these measurements model pipes will be built by the SME partners. Voicing experiments will be performed in the laboratory with the participation of skilled voicers of the selected SME partners.

Sub-task 1.1.3: Voicing with open foot or normal foot bore. (Ruff, IBP)

Voicing by open foot (large foot hole diameter) is preferred by some organ builder, but vehemently rejected by others. An obvious advantage of open foot voicing is the reduction of the variable parameters of one. However, open foot voicing would require different flue width and cut-up scaling as traditional voicing with more closed foot.

Stationary spectra, attack transients and pressure build-ups in feet of pipes having identical shape and dimensions but different foot hole diameter (and flue width) will be measured. Average jet velocity at the flue and pressure in the foot will be determined by stationary measurements. Differences between attacks of pipes with open foot and more closed foot will also be investigated. The optimal scaling of the flue and cut-up will be determined for open-foot voicing.

The objective of investigations was to compare two different methods of voicing by objective measurements and subjective assessments.

Work carried out:

Stationary spectra, attack transients and pressure build-ups in feet of pipes having identical shape and dimensions but different foot hole diameter (and flue width) have been measured. Average jet velocity at the flue and pressure in the foot has been determined by stationary measurements. Differences between attacks of pipes with open foot and more closed foot has also been investigated. The optimal scaling of the flue and cut-up will be determined for open-foot voicing.

The objective of investigations was to compare two different methods of voicing by objective measurements and subjective assessments.

General conclusions of the measurements: It is possible to voice a similar sound with open foot hole in comparison to closed foot voicing. By voicing with open foot hole as a tendency the sound will be louder, the fundamental will be stronger and less harmonics occur. On the other hand at low wind pressure a noise-lowering effect occurs and the sound will be more sensitive for over-blowing due to pressure fluctuations. In the case of voicing with closed foot hole more noise arises.

Subtask 1.1.4: Practical solution for tuning with a tuning slot(Fle, IBP, STZ)

Pipes equipped with a tuning slot (Expression) have a specific timbre, which clearly distinguishable from the timbre of clearly cut pipes or pipes having a tuning roll. Pipes with expression were extensively used in Romantic pipe organs and after a long period of omission they will be more and more popular again. The size and position of the tuning slot influences the formant structure of the sound spectrum radiated at the open end of the pipe. However, the tuning slot is also used for adjusting the pitch of the pipe. Therefore the pipe cannot be tuned without changing the sound character.

The effect of the open area and shape of the tuning slot on the formant structure of the sound spectrum will be studied. A new kind of tuning device will be developed, which keeps the opening area constant during tuning. The effect of the new device on the formant

structure will be investigated by measuring model pipes with new kinds of tuning arrangements. These pipes will be designed and built by the SME partner.

Such experiments on the pipe resonator can be carried out by means of computer simulations. This work has been done by partner 3 (BME) and is shown in Deliverable D1.2.

On the other hand the character of the spectrum changes (8-9-10th partials) with the length of the tuning slot. These character changes should be avoided with a new kind of tuning arrangement.

Subtask 1.1.5: Practical solution for tuning stopped metal pipes with soldered cap (STZ, Fle)

Stopped metal pipes with soldered cap are tuned by bending the ears at the labium. In this way, the effective open area at the labium can be changed, and the pitch changes because of the modified end correction of the pipe. However, this tuning method influences the formant structure of the pipe very much. A better tuning method will be developed and tested by laboratory experiments for separating the tuning from the mouth area.

Task 1.2: Computer simulation of the tuning slot (BME)

Sound radiation of flue pipes is very complex, affected not only by acoustical, but also by flow parameters. In order to reduce the complexity of the problem, a representative detail of the entire sound generating mechanism will be selected for numerical simulation. The eigenfrequency structure of a flue pipe resonator is a predominant component of the radiated sound spectrum and especially convenient for numerical simulations. The resonator frequency response to external acoustic excitation will be modelled by means of the Boundary Element Method. The effects of differently scaled and positioned tuning slots on the resonance frequency and frequency response will be examined by computer simulations.

The sound generation of an organ pipe is a very complex physical process, since the acoustical phenomena take place coupled with fluid flow effects. Even so, by modeling the organ pipe merely as an acoustic resonator, one can predict several key parameters of the sounding with sufficient accuracy. In the course of the work performed in the report period (first year of the INNOSOUND project), the organ pipes have been modeled by means of various numerical techniques. Commercial and self-developed software packages were used, and the obtained data were compared with analytical solutions and measurement results. Some results are shown in the figures 1.5 and 1.6. The developed simulation methodologies

were used for a variety of pipe types. It was shown that by using these techniques one can approximate key acoustic parameters of the sounding characteristics.

Making use of the simulation results geometry parameter sets can be determined, whereby the desired sounding characteristics can be achieved. The final aim of this task was the development of pieces of software that can help the organ manufacturers finding the optimal scaling and voicing for various pipe types and save quite some time in the industrial process of organ builders.

WP2: Special devices

Task 2.1: Analysis and improvement of the impact of nicks on the pipe sound. (Klais, IBP, STZ)

Sound of pipes without and with nicking will be investigated in the anechoic room of IBP. The pipes will be voiced without nicks in the laboratory by a voicer of the SME partner Klais. Attack and stationary spectra will be measured and then the voicer will make nicks into the edge of the languid. Then the spectra will be measured again. Thus the changes of pipe sound due to nicking could be identified and analysed. Different pipe ranks will be studied and different nick shapes and sizes will be investigated. The influence of nicks will be studied by means of temporally resolved Schlieren flow visualization technique.

After clearing the effect of nicks on pipe sound an optimal nicking technique will be developed for pipe types defined by the SME partners in WP1.

Several pipes have been built for these experiments by the SME partners. Investigations have been carried out in the anechoic room of the IBP with different voicers.

It is very characteristic, especially for metal pipes in the 1' and 2' stops, that nonharmonic sharp peaks occur on the sides of high frequency partials. These components give a roughness and a metallic character to the timbre. It was assumed that these additional peaks can be assigned to wall vibrations, but recent investigations revealed that this phenomenon is probably caused by the excitation of higher eigenmodes by a higher component of the edge tone. This effect can be avoided by properly adjusting the edge tone, or by reducing the levels of the higher eigenmodes by nicking.

Spectra of a 2 feet c Diapason pipe a) without nicks b) with nicks The harmonic partials are marked by v-shaped cursors

The nicking e.g. the small cuts in the edge of the languid produce vertical vortex lines, which stabilize the jet and reduce the turbulence. The broadband noise in the steady spectrum decreases in the range of the higher partials. On the other hand, the attack will be somewhat slower.

Task 2.2: Analysis and improvement of the impact of ears on the pipe sound. (Fle, IBP, STZ)

The aim of this task is to clear the influence of the ears on the pipe sound, to develop better ear constructions and to optimize the utilization of ears in voicing practice.

The effect of different kinds of ears on the attack transient and stationary sound will be investigated by laboratory measurements of model pipes provided by the SME partner Fle. Ear effects on the acoustic resonator and on the mouth tone will also be investigated in the laboratory. After clearing the role of the different ear constructions new, improved ear types will be developed and optimized for the voicing practice of organ building.

1.1 Measurements

Acoustical measurements have been carried out with some flue organ pipes [2.2, 2.3]. This time, two real organ pipes were used for the measurements. They are scaled relatively narrow and belong to the string family. Since movable ears were applied to them, two conditions, with ears and no ears, were available. Additionally, the box-type ear was also applied. This ear adds another (horizontal) plate to the lower lip to usual type of the ear. The height of the ear plate is 12 mm, since organ builders generally use about one forth of the mouth width for ear height. Although normal blowing pressure of these pipes was 590 Pa (60 mm Aq) measured in the wind chest just below the foot, the blowing pressures about 8% above and below this normal pressure were also used. Therefore, a combination of three types of ears and three values of blowing pressure were examined.

To investigate both the steady state and the attack transient, the sound recording, pressure measurement, mouth tone recording, and eigenmode measurement were carried out in an anechoic room with a small pipe-organ mechanism.

First acoustical measurements were carried out to investigate the effect of the ears with real organ pipes. The following phenomena were observed:

In the steady state,

- A slightly lower sounding frequency (a growth of the effective length of the pipe).
- An increase in the level of the fundamental (simultaneously, the depression of the harmonics).
- A shift of the minimum position in the spectral envelope toward the lower harmonic.

In the attack transient,

- A faster attack time.
- A more stable attack transient (a substantial decrease in the standard deviation of the attack time).
- A significant coupling with mouth tone.

From the above, the recognition of the organ builders is confirmed by our investigations in a more visible and quantitative fashion. It is possible to say that the ears make the sound more fundamental. Further measurements investigated the effect of different ears to a more detailed way.

Task 2.3: Investigation and improvement of the air flow in pipe foot (Blanc, IBP, STZ)

The attack transient of a flue organ pipe is mostly influenced by the edge tone, which is mainly determined by the configuration of the mouth as well as by the condition of the air flow inside the pipe foot.

Sub-Task 2.3:1: Investigations of the flow condition in the foot by a foot model

In order to study the influence of the flow condition in the foot on the stationary sound of organ pipes, a 3-dimensional rectangular pipe foot model with attachable pipe body will be built by partner Blanc. Without attaching the pipe the properties of the air jet emerging from the flue can be investigated. The build-up of the sound can be studied by attaching the pipe body to the foot model.

Jet velocities, outflow directions and velocity fluctuations will be investigated without the diverter and with diverter built in two different positions. The goal of these investigations is to determine, which arrangement provides the smallest velocity fluctuations.

Sub-Task 2.3:2: Optimization of the pipe sound by flow diverter.

Acoustical measurements will be carried out in the anechoic room on different pipe types with and without built-in diverter in the pipe foot. Both attack transients and stationary spectra will be measured. The diverter will be applied in the best position determined in Sub-task 2.3.1. The pipes for the experiments will be provided and prepared for the measurements by partner Blanc.

Pipe constructions with built-in flow diverters will be designed by IBP, STZ and Blanc for practical use in organ building. The new constructions will be tested in the laboratory.

Task 2.4: Investigation and improvement of the air inflow to the foot of wooden pipes. (MühLe, IBP)

Pipe foot constructions with improved fluid mechanical properties will be designed and optimized by a successive improvement process using measurements, fluid mechanical considerations and requirements of the organ builders. The optimized foot geometry will be tested by laboratory investigations and flow visualization.

Velocity measurements, flow simulations, acoustic recordings and analyses have been carried out for 6 different geometries of the foot and wind chamber of a wooden pipe. The traditional case is an empty wind chamber and a pressure control screw in the (short) pipe foot. The other cases were created by changes of the original geometry.

The acoustic measurements showed that there is clearly audible flow noise in the stationary spectrum mainly due to the interaction of the free jet leaving the flue with the upper lip. The interaction between jet and upper lip seems to depend on the velocity profile and jet turbulence. How this dependence looks like in detail could not yet be explained by the present investigations. It was assumed that turbulence influences the jet width and therefore the location of the upper lip relative to the jet profile. For that reason the jet angle had to be corrected in case 6 by lowering the cap of the chamber.

Jet turbulence could be reduced by an extension of the pipe foot with increase of the distance between screw and wind chamber. The lowest turbulence and most balanced

velocity profile could be reached by application of a vertical separator and honeycomb material in the chamber.

It was shown that the number of partials in the stationary spectrum and their build-up speed is influenced by different geometries. If a fundamental-based sound (few partials) with less flow noise and slow attack is desired, the solution with long pipe foot should be preferred. If a bright sound (a lot of partials) with fast attack is needed, the geometry with vertical separator and honeycomb should be preferred. In this case the position of the cap must be carefully adjusted in order to reduce flow noise.

Case 1 Front view Cross section empty wind chamber geometry, with open and short pipe foot (screw for pressure control removed)

Case 2 Front view Cross section empty wind chamber geometry, short pipe foot, with screw for pressure control (50% closed) widely used in organ building

Case 3 Front view Cross section empty wind chamber, long pipe foot with screw 50% closed innovation:

distance between screw and chamber is increased

Case 4 Front view Cross section diagonal wind diverter towards the flue, screw 50% closed similar geometries are used by some organ builders

Case 5 Front view Cross section two chambers with horizontal separator, short foot with screw 50% closed

Case 6 Front view Cross section two chambers with vertical separator and honeycomb material, short pipe foot with screw 50% closed innovation:

application of honeycomb material

See more details in Deliverable 2.1.

WP3 Special pipes

Task 3.1: Development of optimal scaling of the depth and width of wooden pipes.

In case of wooden pipes the reduction of pipe width would be desirable, because the space requirement of the pipe organ could then also be reduced. On the other hand, the sound quality could be worse for too narrow pipes. The aim is to find the narrowest scaling of wooden pipes with still appropriate sound quality.

Sub-task 3.1.1: Laboratory experiments (Ofic, Boog, STZ, IBP)

Optimal scaling of the depth and width of wooden pipes will be developed in order to help the design of the instrument to the space requirements of the room. A series of differently scaled wooden pipes will be acoustically investigated in the anechoic room of the IBP. On the basis of the results a design and scaling method will be developed that can take into account the effect of wall dimensions, material and finish on the stationary spectrum of the sound.

Sub-task 3.1.2: Computer simulation of wooden pipe forms (BME)

The eigenfrequencies of the pipe resonator will be numerically simulated by means of the Finite Element Method and/or of the Boundary Element Method. The influence of the depth and width of wooden pipes on the formant structure of the stationary sound will be investigated and optimized. The results of the simulations will be used in Sub-task 3.1.1.

Sub-Task 3.1.3: Design software for the optimal scaling of wooden pipes (IBP, BME)

On the basis of the elaborated method in Sub-task 3.1.1 design software for the optimal scaling of the depth and width of wooden pipes will be developed. With the help of the software the organ builder can optimize the dimensions of the wooden pipes with the aim to reduce the length and so the price of the wind chest, but maintaining an optimal sound quality in the same time.

Development of optimal scaling of the depth and width of wooden pipes

In case of wooden pipes the reduction of pipe width would be desirable, because the space requirement of the pipe organ could then also be reduced. On the other hand, the sound

quality could be worse for too narrow pipes. The aim is to find the narrowest scaling of wooden pipes with still appropriate sound quality.

Laboratory experiments

Optimal scaling of the depth and width of wooden pipes has been developed in order to help the design of the instrument to the space requirements of the room. A series of differently scaled wooden pipes has been acoustically investigated in the anechoic room of the IBP. On the basis of the results a design and scaling method have been developed that can take into account the effect of wall dimensions on the stationary spectrum of the sound.

Computer simulation of wooden pipe forms

The eigen frequencies of the pipe resonator have been numerically simulated by means of the Finite Element Method and/or of the Boundary Element Method. The influence of the depth and width of wooden pipes on the formant structure of the stationary sound has been investigated and optimized.

Design software for the optimal scaling of wooden pipes

On the basis of the elaborated method design software for the optimal scaling of the depth and width of wooden pipes has been developed. With the help of the software the organ builder can optimize the dimensions of the wooden pipes with the aim to reduce the length and so the price of the wind chest, but maintaining an optimal sound quality in the same time.

The innovative calculation method can be described by the following steps:

- 1) A new (smaller) width is calculated by a constant factor $F_{wmod} (< 1)$
- 2) The corresponding new depth is calculated so that the loss factor of both cross sections is equal

Definition of loss factor:

Where: P perimeter, A cross section, δ boundary layer thickness

The loss factors are equal for:

Where: and

The relation for the new depth is:

Task 3.2: Development of optimal scaling of the chimney and the pipe resonator of chimney flutes

Optimal scaling and design of chimney flutes will be developed by means of appropriate laboratory experiments and computer simulations. Design software will also be developed for the optimal scaling of chimney flutes..

Sub-task 3.2.1: Laboratory experiments (IBP, STZ, Klais, Porg)

Stopped pipes produce mostly odd harmonics; the addition of a chimney adds more even harmonics to the sound. The length and diameter of the chimney varies considerably from builder to builder. The real effect of the chimney on the sound is not known and a method of sound design does not exist until now. Therefore, organ builders cannot utilize the possibilities of this complex pipe form. Because of this it is crucial to investigate the function of the chimney in the sound articulation of the pipe.

A series of differently scaled chimney pipes will be acoustically investigated in the anechoic room of the IBP. The measurement results, together with the results of computer simulations of Sub-task 3.4.2 will be used for developing a design method of chimney pipes, which takes into account the properties of both acoustical systems and provides an optimal matching of them. New voicing and tuning methods will also developed for the new chimney pipe constructions.

Sub-task 3.2.2: Computer simulation of chimney pipes (BME)

The pipe resonator and the chimney form a coupled acoustic system. The eigenmodes of such a coupled acoustic system will be numerically simulated by means of the Finite Element Method and/or of the Boundary Element Method. The influence of the length and diameter of the metal tube (chimney) on the formant structure of the stationary sound will be investigated and optimized. The results of the simulations will be used in Sub-task 3.2.1.

Sub-Task 3.2.3: Design software for optimal scaling of chimney flutes (IBP, BME)

On the basis of the elaborated theory in Sub-task 3.2.1 a design software will be developed for the optimal scaling of the chimney and the pipe resonator of the chimney flute, for providing the desired sound quality and timbre.

The idea of adding a chimney (smaller tube) to a normal metal pipe (Fig. 3.5) is to emphasize a defined partial in the stationary sound spectrum of the pipe. In practice, the diameter and length of the chimney are calculated by a constant factor depending on the diameter of the main pipe.

This method, however, cannot ensure the same sound spectrum over the whole frequency range. For this reason an optimization method was developed for the lengths of main pipe and chimney.

Steps of the optimization process:

- 1) Preliminary calculation of lengths and diameters of the main pipe and tube, using traditional scaling methods
- 2) Decision, which partial is to be emphasized in the stationary spectrum
- 3) Optimization of the lengths of main pipe and tube using the innovative calculation, so that the selected partial is emphasized for all semitones

Traditional calculation method for the tube:

Description of the calculation method:

For acoustical calculation the coupled system of main pipe and chimney is modelled by an input admittance function, which is expressed as the reciprocal of the total impedance Z_{sys} of the system:

Definition of the partial impedances:

Here R means the radius of the pipe and R_t the radius of the chimney tube, k is the wave number, ρ the air density and c the speed of sound.

In the stationary spectrum all frequencies matching the eigenmodes of the chimney pipe (peaks of the admittance function) will be amplified. This means that for any partial frequency to be emphasized the lengths of both pipe and chimney must be changed until an eigenmode frequency of the pipe equals this defined partial frequency (example see Fig. 3.7). Because of the high computational costs an optimization algorithm found by Nelder and Mead [5] is used and the cost function is defined as:

Here W_f and W_h stand for weights of the error of the fundamental and harmonic eigenmode frequency. f_1^* denotes the desired fundamental frequency. For the starting point of the optimization process, the dimensions of the traditional calculation can be used.

WP4 Transitions

Task 4.1: Analysis and improvement of transitions between two different pipe types

Sub-Task 4.1.1: Transitions between wooden and metal pipes (Schu, Ruff, IBP)

Instead of the sudden transition a gradual one through N pipes will be applied. The number N of the pipes of the transition is defined in WP1. Gradual transition between typical stopped wooden pipe spectra and open metal pipe spectra will be achieved by changing the wooden pipe spectra gradually from the stopped character to open character up to the last wooden pipe. The first metal pipe will be scaled and voiced for fewer overtones, and then the amplitudes of overtones will be gradually increased to the typical spectrum of an open metal pipe of that rank.

This solution will be achieved by investigating different wooden stopped and metal open pipes in the anechoic room of IBP. Geometrical parameters needed for equalising timbre at transitions within a single rank will be determined. Rules for transitions between wooden and metal pipes will be developed.

The pipes will be built and practical assistance will be provided by partners Schu and Ruff.

Sub-Task 4.1.2: Transition between chimney flute and stopped pipes (Porg, IBP)

Instead of the sudden transition a gradual one through N pipes will be applied. The number N of the pipes of the transition is defined in WP1. Gradual transition between typical

stopped metal pipe spectra and chimney flute spectra will be achieved by changing the stopped pipe spectra gradually from the stopped character to the character of the chimney flutes.

Different chimney flute and stopped metal pipes will be acoustically measured in the anechoic room of IBP. Geometrical parameters needed for equalising timbre at transitions within a single rank will be determined. Rules for transitions between stopped and chimney pipes will be developed.

The pipes will be built and practical assistance will be provided by partner Porg.

The new scaling methods will be used in Task 4.2. for developing a software for dimensioning the pipes.

Task 4.2: Design software development (IBP, STZ, BME)

The developed methods of progressive scaling at transitions will be used for the development of a software tool for organ builders. The input data of the software tool will be the scaling information of both stops, the position of the transition, and the number of pipes in the transition range. The software will calculate the scaling and other design data of each pipe in the transition range.

Scaling of transitions

Transitions can be defined in the INNOscale software as stop property. After creating a new stop the window "Stop properties" can be opened by right clicking with the mouse on the stop name:

As described in Sec.7: "Stop properties and scaling tables" (Annex 1, pages 15-17), the "number of transitions" is a basic parameter of a stop. Its default value is "0". In the default case only one "Rank" column appears in the "Visible parameter" table, and the "Properties of transitions" table cannot be seen.

Maximum 3 transitions can be selected in the "Footage, range and transition properties" table:

When a number n is selected, the "Visible parameters" table will contain $n+1$ columns for the different ranks within the stops.

By selecting 2 transitions 3 columns appear in the "Visible parameter" table:

For each rank a pipe type has to be selected among the presently available 9 pre-defined pipe types.

Available pipe types:

- metal / open / cylindrical
- with expression (metal / open / cylindrical)
- metal / open / conical
- metal / stopped
- wooden / open / straight
- wooden / open / conical
- wooden / stopped
- chimney flute / metal
- chimney flute / wood

The "Properties of transitions" table appears, too, with n rows for defining the semitone positions of the transitions, and the number of pipes at both sides of the transition.

For example, in the case of one transition the table appears with one row. The location of the transition has to be given by selecting the octave and the semitone position of the transition within the selected octave. Then the number of the pipes on both sides of the transition has to be selected among the whole numbers 1 - 6. In the presented case 3 pipes are selected:

After completing Table "Stop properties" and pushing the "OK" key the scale diagram and the table with the selected parameters of the stop appear. The data of the pipes of

transition are marked with yellow. Since the scaling curves in the INNOscale software must start and end at a C note, the scaling curve of the first rank ends at the first C-note after the transition, while the scaling curve of the second rank starts with the last C-note before the transition.

The calculation of the pipe dimensions by INNOscale is performed in the full range of the rank. However, only the data up to the last pipe before the transition are relevant for Rank 1, and the data from the first pipe after the transition are relevant for Rank 2.

2 Calculation of transitions

The design of transition is a very complicated task, which cannot be fully automated. The organ builder decides, what type of pipes will be used in the different parts (called "Ranks" in INNOscale) of the stop, and he/she has to define the scale of these Ranks. Moreover, he/she has to decide, which location(s) will be used for the transition. These decisions depend mostly on the required properties of the planned pipe organ, on the acoustics on the room and the personal taste and experience of the organ builder. This complicated planning activity results in individual scaling curves for the different ranks of the stop, similar to the two scaling curves shown in the above figure.

The calculation function regards the first and last pipes of the transitions as fix points on the scaling plot and calculates the data of the other pipes by linear interpolation between the fix points. By this method the stationary spectra of the two ranks can be brought closer to each other.

The attack transient of the pipe sound is also very important in the perception of pipe sound. The scaling of the transition cannot ensure the proper attack of the pipes; therefore the attacks of the pipe sounds at the transition have to be adjusted by a skilled voicer.

WP5 New timbres

Task 5.1: Development of new kinds of organ pipes with user-defined sound.

Partners: MuStra, Klais, STZ, IBP

RTD partners will design organ pipes for sound characters defined by the SME partners in WP1. Knowledge about the physics of organ pipes will be applied for determining the shape and size of the pipe, the wind pressure in the foot and the adjustments of the mouth parameters to get the sound character(s) pre-defined by the SME partners. The designed pipes will be built by SME partners and will be tested by measurements in the laboratory and by listening tests.

At the end of Task 5.1 a decision will be made (Milestone 2 of the project) about Task 5.2. The software design tool will be developed only if the quality of the user-defined new sounds meets the expectations of the SME partners, and they intend to introduce the new pipe sorts into their pipe organ products.

Task 5.2: Software tool for designing pipes with user-defined sound.

Partners: IBP, STZ, BME

This Task will only be carried out when Task 5.1 is successfully completed. The goal is to develop a design tool for the SMEs that can be used for determining the pipe shape, calculating the pipe dimensions and for suggesting voicing steps in order to achieve a pre-defined sound character.

The knowledge resulted from the project about the role of the resonator eigenmodes, the overtones, the mouth tones and the formant structure of the spectral envelopes on the sound of organ pipes has opened the possibility to design of the sound character of a labial organ pipe to a desired timbre.

Three methods were developed:

- matching of the eigenmodes of the resonator and the harmonic partials of the pipe sound,
- planning of the formant minimum to a selected harmonic partial,
- matching of the mouth tone frequency to a selected partial.

These methods are built into the developed scaling software and can be used by the organ builders to design the timbre of their labial organ pipes.

Description of the experiments and results of measurements

The description of the experiments and the measurement results are presented in D5.1.

Short summary of results

From the standpoint of acoustics, an organ pipe is an acoustic resonator with several eigenresonances. The resonator can amplify sound at its eigenfrequencies. In the case of an open cylindrical organ pipe the eigenfrequencies are nonharmonic; they are slightly stretched. This behaviour can be observed in the measured sound spectrum of an open pipe by comparing the positions of the narrow lines of the harmonically spaced partials with the broad profiles of the eigenresonances.

The amplification of the partials of the steady sound of the pipe depends on the relative position of the partial and the eigenresonances. Maximal amplification can be achieved, when the partial sits on the peak of an eigenresonance. On the bottom of a valley between two eigenresonances the partial is not amplified; therefore a minimum occurs in the spectral envelope in such cases.

The eigenresonances are stretched, compared to the odd partials of the pipe sound. The 5th and 7th partials are very weak, because they are close to minimums between two eigenresonances.

In this case the eigenresonances of a stopped wooden pipe was tuned by boring a hole in the stopper. By changing the diameter of the hole the eigenresonances can be tuned downwards in frequency. An almost perfect overlapping of the first four eigenresonances with the odd partials was achieved. The 5th partial is amplified by 20 dB, the 7th one by 8 dB due to the better overlapping. The sound becomes more colourful.

A similar effect can be achieved by chimney pipes by tuning the length of the chimney. In this case not only the eigenresonance frequencies can be tuned. The chimney acts as an acoustic filter and therefore a selected partial can be attenuated by tuning the length of the chimney. For more information see Annex I.

By tuning the formant minimum (by changing the open area of the mouth) a sharp minimum was achieved at the 3rd partial, as shown in Fig. 5.5.

The method of attenuating selected partials by tuning the formant minimum can be applied very effectively on pipes having a tuning slot (expression). In this case the formant minimum

at the labium and at the tuning slot can be adjusted separately by changing the open areas of the openings. Such a way a desired formant shape can be planned by the organ builder.

The above discussed two methods can be used for adjusting the timbre of the stationary sound. The third method, the adjustment of the edge tone frequency, can be used for adjusting the attack transient of the pipe. The frequency of the edge tone is tuned to the frequency of a harmonic partial of the pipe sound. In this case this partial can be heard at the beginning. After a while the fundamental component of the sound will be the strongest partial, and the normal pipe sound can be heard. The transition from a higher partial (a third or a major fifth in musical sense) to the fundamental may provide a very beautiful sound. The best effect may be achieved by tuning of the edge tone frequency to the selected partial, and by tuning the eigenfrequencies such a way, that the selected partial sits in a valley. In this case the selected overtone can be heard clearly in the attack, but it disappears gradually, and it is missing from the steady sound.

The new methods for designing the sound character of organ pipes are included in the developed new software. More detailed description of the applied design and calculation methods are given in D5.2: "Software Code: New Timbres".

WP6 Validation

Task 6.1: Validation

Partners: Mühle, Schu, Ofic, Ruff, Klais.

The new voicing, tuning and scaling methods as well as the new devices and pipe designs developed and optimized in WP2-WP6 will be validated by the SME partners in their own workshops. Pipes will be built, voiced and tuned by the SME partners to check the suitability of the new constructions and methods in organ building practice. The results of the validation will be discussed by the RTD partners who developed the investigated new constructions and methods. Necessity for further improvements and optimization will also be identified.

Validation of the developed software tools

WP7 Optimization

Task 7.1: Optimization

Partners: MühLe, Ruff, Schu, IBP, STZ, BME

Problems identified during validation will be discussed among SME and RTD partners and the new methods and/or constructions that need further optimizations will be identified. Improvement and optimization will be carried out by the RTD partners. The optimized methods and/or constructions will be validated again by the SME partners.

WP8 Training

Task 8.1: Presentation of the results and training of the new methods

Partners: All partners

The RTD partners of the project will present the results of the RTD work performed in WP2-WP6 and give a detailed explanation of the developed new constructions, tuning and voicing devices and methods.

The SME partners responsible for the validation and optimization of the respective results (WP7) will present and comment their results and experiences. New pipes built and voiced according to the developed new scaling and voicing methods will be presented and compared to traditional pipes. The presentations will be organized in the frame of a workshop at the IBP, where comparison measurements will also be carried out and presented to the SME partners.

Task 8.2: Presentation of the results and training of the new software

Partners: All partners

Software tools developed for supporting the practical work of the organ builders will be presented, and the participants of the workshop will be trained to the use of those tools.

Selected staff of the individual SME partners (organ builders, voicers, pipe makers and designers) will participate on the training. The participants of the training can gain hands-on experience on the new methods by voicing and tuning organ pipes according to the developed new methods.

Potential Impact:

Improvement of SME competitiveness:

The new, scientific voicing, tuning and scaling methods for manufacturing specific critical pipes and pipe ranks for pipe organs and the software tools for dimensioning pipes and pipe transitions improve the sound quality of the organs produced by the SME partners of the project. The improvement of the sound quality leads to a competitive advantage, because a high opinion of the sound quality of a completed pipe organ helps to receive new orders. The best advertisement in organ building is always the quality of the products. Since the participating SMEs were involved in the research, and their employees were trained to the new methods and to the use of the software tools by the training course in WP8, they could introduce the new methods and pipe constructions into their practice well before disseminating the results for the whole sector.

The reduction of the production costs by better design and less working hours of voicing adjustments can be regarded also as a competitive advantage. An overall reduction of 10% of the production costs of the pipes can be expected.

Besides the reduction of the production cost at the SME beneficiaries, the results of the proposed project, namely

- the software tools for the design of the dimensions of wooden pipes and chimney flutes as well as transitions between two pipe types within a single rank,
- the know-how of the new voicing, tuning and scaling methods for better sound quality,
- the know-how of the new method and the software tool for designing innovative organ pipes for user-defined sound character,

can also be used by the participating SMEs for developing new pipe organ products with improved sound quality. On one hand, traditional pipe ranks could be developed with improved sound quality (chimney flute stops, stops with expression, improved wood pipe stops, etc.), on the other hand new sort of pipe ranks could be developed for desired, pre-defined sound character. The application of improved traditional stops in the pipe organs will provide a competitive advantage for the partner SMEs on the European and North American market.

Pipe ranks with user-defined sound character could open new markets for organ building. Recently, the Asian countries show more and more interest to pipe organs. A few decades ago, no pipe organ could be found in that countries, while nowadays plenty of instrument

can be found, or are under construction in Japan, China, South Korea, etc. Several partner SMEs of this consortium are already active on the Asian market.

In the course of the development of organ building tradition (in the 16-19th centuries) pipe ranks have been developed for imitating the sound character of diverse musical instruments used in Europe. The names of the stops show, which sound was targeted, thus there are stop names like Flute, Recorder, Violone, Gamba, Transverse flute, Trumpet, Oboe, etc. During the last 100-120 years no new pipe ranks have been developed any more.

On the Asian market it would be an advantage, if the organ builder could offer pipe ranks with similar sound characters as the sounds of the local musical instruments. The results of the project will provide the know-how to develop pipes with the desired sound character. The SME partners could implement the new know-how in their production in 3-5 years after completing the project.

European dimension - technology transfer

Organ building is a traditional European industry, which has developed different traditions in different regions of Europe. Although, more recently, organ building became more international, marked differences can still be found between regions in the preferred sound character. The different traditions can be analysed scientifically and be utilized in the project only if reliable organ builder SME-s of the most important European regions, which still practise these traditions, will be involved in the project. This goal could be achieved only on a European level, i.e. by including at least one partner from each important region into the project.

It is very seldom that organ builders from 8 European countries have the possibility to meet regularly to discuss technical matters. Through the organisation of training courses and regular technical meetings, the project improved the technological co-operation among SMEs and with the participating research institutions. This has encouraged the knowledge transfer between scientists and organ builders in this traditional sector on a European level.

Contribution to EU policies

The European social and economic cohesion had benefit from this project associating 13 partners from 8 Member States.

Since the organ building tradition belongs unambiguously to the European cultural heritage, the scientific analysis of traditional pipe ranks and voicing, tuning and scaling techniques correspond to the policy of "Protection and conservation of European cultural heritage."

The project has also contributed to the 'Research for SMEs' initiative of the 7th EC Framework programme especially for a very traditional sector. To this sector belong about 750 micro enterprises in Europe. The project also strengthened and helps to structure the European Research Area (ERA) in the domain of acoustics research for music instruments. The leading European institutes in this field were present in the consortium. The project has played the role of a catalyst, by bringing together the different academic and industrial actors, from the scientist of fundamental research to the engineer or technician of organ building SMEs. Moreover the planned dissemination of the results of the project in the Organ Builders Community corresponds to the EU policy "Dissemination of best practices".

Quality of life and health and safety

-By improving the quality of the sound of pipe organs the project indirectly contributed to the quality of life, because listening to organ music and attending organ concerts belong to the favorite pastime of the people.

-Due to the better sound quality the organ music played on social events, such as church services and in concerts will be more enjoyable. It can result a better relaxation for the people, whose life is generally full of stress.

-Due to the reduction of costs of pipe organs more churches and concert halls can afford to build new pipe organ thus more people may have the possibility for a good relaxation.

Employment and level of skills

-The cost reduction and quality improvement due to the application of the results of the project can improve market position of the participating SMEs, which could be manifested in the increasing number of orders of new instruments. In this case the SMEs will increase the number of their employees. The leading position of the European organ builder SMEs on the world market will be strengthened.

-Organ building is an extremely difficult work. Organ builders are very skilled craftsmen with highly developed hearing. Their work could be regarded as a kind of art, because a lot of intuition and musical feeling are needed for producing the required character of the sound. On the other hand, voicing of thousands of pipes in a church or concert hall is a repetitive and very time consuming work. For this reason voicing could be not very motivating, even boring work for the employees. Moreover, the physical and especially the psychic condition of the voicer can negatively influence the quality of his work. Therefore, a better understanding of the role of voicing steps and a better scaling of the pipes may facilitate the

work of organ builders, and a more conscious application of the scientific results in the everyday work may help to improve the level of skill in organ building.

- The application of the new voicing, tuning and scaling methods will further improve the level of skill of organ builders. The level of skill of young organ builders can be improved by applying the new knowledge in the training of apprentices.

- The level of skill of pipe organ design will be significantly improved by the application of the new, scientific voicing, tuning and scaling methods.

- The training for the use of the new software tools will improve the skills of the employees in the traditional sector of organ building SMEs.

The dissemination of the results will be carried out in two phases:

1.The results of the co-operative research project will be disseminated for not participating organ builder SME-s and organists without revealing sensitive manufacturing information through:

- Papers to be published in journals of musical instruments and organ building (Instrumentenbau Zeitschrift, Das Musikinstrument, ISO Journal, Ars Organi, etc.)

- Presentations on international conferences (International Symposium on Musical Acoustics, ISO meetings, etc.),

- Short courses and workshops organized by the IBP for introducing the new voicing, tuning and scaling methods and software tools. These courses will be open for everybody (start: 3 years after the project).

- The intensive courses of organ acoustics, organized yearly by the IBP. The new results will be included to the curriculum of the course.

- The presentation of the public project results on a dedicated webpage on the webpage of the coordinator and with link to this page on the website of the other project partners.

2.Public results of the laboratory measurements will be published in journals of organ building and organology, in scientific journals and at conferences. (Since the measurements would reveal the relationship between traditional voicing, tuning and scaling rules and measurable acoustic properties, organ builders and organ experts are certainly interested in these results.)

This dissemination strategy can ensure the free access of everybody to the results of the project without endangering sensitive manufacturing information and can maintain the

competitive advantage of the participating SMEs for about 3 years after completing the project.

List of Websites:

http://www2.ibp.fraunhofer.de/akustik/Orgelsound/index_e.html