Digital Intelligence Organology (DIO): Physical Modelling of Musical Instruments

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KURZDARSTELLUNG: Organology has a wide range of approaches to classify and study musical instruments. One important aspect is the sound generation in the instrument. This is normally studied by carrying out acoustic measurements. Exemplary we present investigations of the trumpet, the recorder and the organ pipe. A new approach is to utilize numerical simulations that map the fluid dynamics as well as the interaction with the emerging sound field. The numerical approach is demonstrated at the organ pipe. Utilizing numerical simulations solving the compressible Navier-Stokes equations with suitable boundary and initial conditions, it is possible to redraw the generation, the propagation, the reflection, the damping and the radiation characteristics of sound waves. The focus of the study is on the occurring pressure wave fronts in the initial transient. These special wave fronts show shock wave characteristics. Subject of interest is their contribution to the formation process of the sound field inside the resonator. Utilizing spectral analysis as well as extended visualization methods, a wide range of aspects of the dynamics of the initial transient of the organ pipe is discovered. The nonlinear damping processes in the resonator are discussed. The numerical approach presented in this case study, allows to study the initial transient of the organ pipe with an new level of precision. It can help to understand the basic physical principles of sound generation and the mutual interaction of the flow field and the sound field inside the musical instrument and similar wind instruments that produce complex sounds.

1 ACOUSTIC MEASUREMENTS

1.1 TRUMPET

The acoustic measurements of the transient of the trumpet have been done with a linear microphone array with 4 microphones (iSEMcon EMM-7101). The distances of the microphones were 0mm, 152mm, 298mm and 451mm in front of the trumpet. The sampling rate was 500kHz. The trumpet was blown on normally by an amateur musician

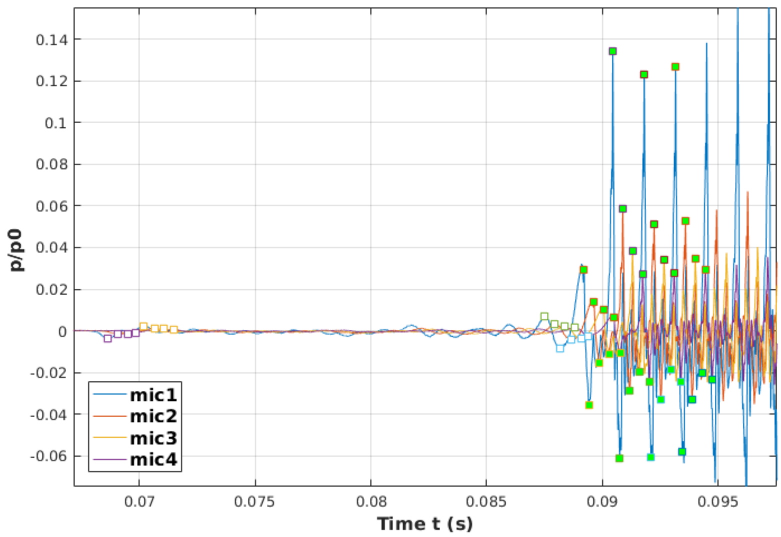

Figure 1: *Signals of the wave front peaks (minima and maxima) recorded at the microphone positions.*

In Figure 1 the received signals at the microphones are depicted. Labelled are the first four maxima and minima of the wave fronts.

(iSEMcon EMM-7101) located at 10 equidistant finger holes, cf. Figure 3a. The distances of the microphones were 50 mm. The measurements were repeated ten times.

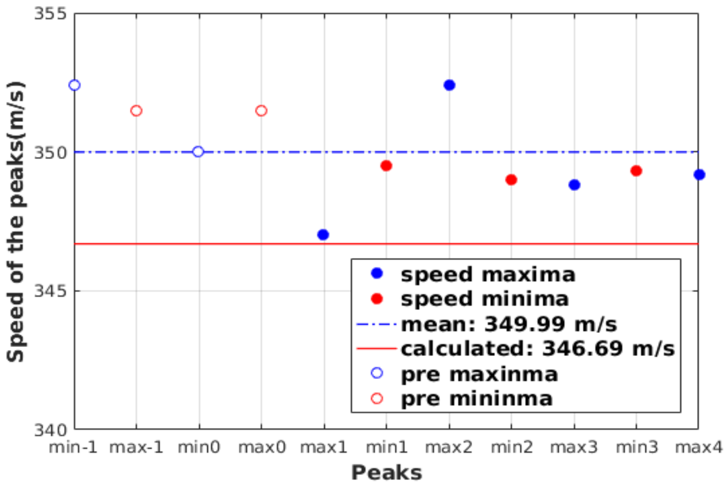

Figure 2 *Velocities of the wave front minima and maxima of the initial transient of the trumpet.*

The analysis of the passing times of wave front minima and maxima at the microphone positions lead to velocities of the propagating wave fronts along the microphone array. Figure 2 shows the corresponding velocities. Note that all measured velocities are slightly higher than the local speed of sound of c0=346.69 m/s, calculated from the measured room conditions. This indicates that the initial wave fronts have shock wave characteristics.

1.2. RECORDER

Similar measurements have been done with a block of a recorder which was connected to a resonator duct with length 500mm. The microphone array consisted of 10 microphones

The data analysis is shown in Figure 3b. Note that the measured velocities of the initial wave fronts which propagate in the resonator are slightly, but significantly higher than the speed of sound.

The acoustic measurements of the transient of the trumpet and the recorder show that in both instruments occur wave fronts that show show wave characteristics. The velocities of the initial wave fronts are slightly higher than the speed of sound. Analogous acoustic measurements have been done for the Turkish Ney and the organ pipe. In the second part numerical investigations of an organ pipe are presented. Before the results are discussed

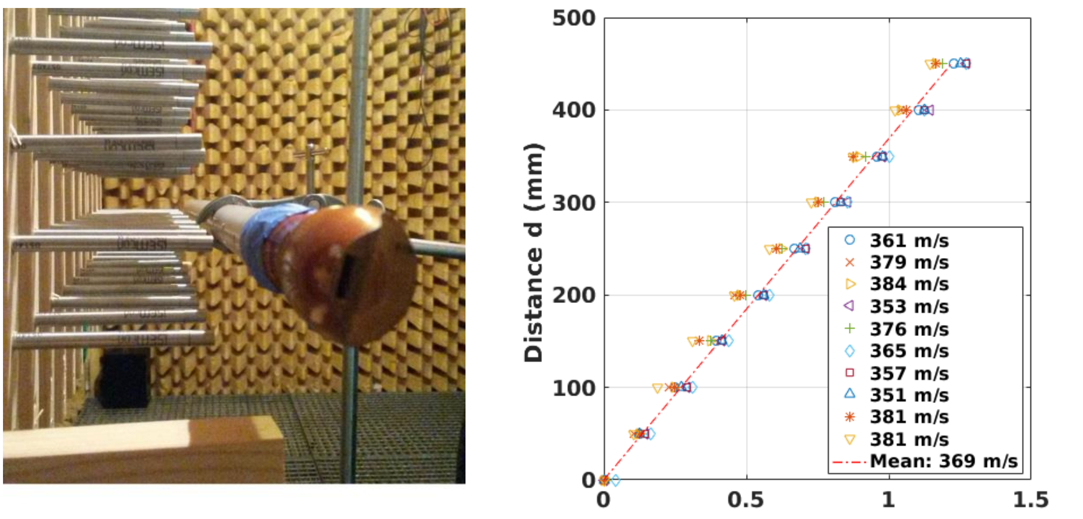

Figure 3 a) *Experimental set-up. b) Velocities of the initial wave fronts. Shown are the results of ten runs of the experiment.*

some general annotations on the numerical implementation and numerical simulation are given.

2. NUMERICAL SIMULATION OF THE INITIAL TRANSIENT OF AN ORGAN PIPE

2.1. GENERAL ANNOTATIONS ON NUMERICAL IMPLEMENTATION AND NUMERICAL SIMULATION

The mutual interaction of the flow field and the sound field, the sound generation and the sound propagation are described by the compressible Navier-Stokes equations [1], [2]. For a successful numerical implementation of the set-up, a wooden stopped organ pipe whose internal air volume is excited to vibrations by a blowing mechanism, one has to apply the compressible Navier-Stokes equations with appropriate initial and boundary conditions. The set of equations have to be solved on an suitable computational grid, the numerical space which is called the mesh. The numerical handling of compressible problems is still an advanced task. The main difficulties arise from reproducing the interactions between the flow field and the sound field [3]. The different time scales of the flow velocity and the particle velocity are difficult to model simultaneously. Numerical simulations allow to study the dynamics of inherent fluid mechanical structures like vortices, jets as well as the generation of sound waves, their propagation in the resonator and their radiation into the free space. A successful modelling and a satisfiying simulation process can be divided into the following sections: The physical previews, the pre-processing, the processing and the post-processing. The sections include following sub-tasks and relate to questions that need to be being answered appropriately:

PHYSICAL PREVIEWS:

- Which set of equations is constitutive for the given problem?
- Which are the characteristic fluid dynamical numbers to be taken into account?
- What are the scales of the problem?
- Software-decision.
- Hardware-decision.

PRE-PROCESSING:

- How to write an appropriate mesh for the given case?
- Determine the relevant thermo-physical properties.
- Implement suitable initial and boundary conditions for each physical quantity to be calculated, e.g. pressure p, the velocity vector U, temperature T , density ρ, turbulent kinetic Energy k, etc..
- Discretization schemes for the differential operators in the constitutive equations (del operator, Laplacian, time derivative, etc.) inclusive proper correctors.
- Select an appropriate turbulence model to model the energy transfer into and out of the sub-grid scales.
- Solver for the compressible fluid dynamical problem, determination of numerical schemes and their tolerances.
- Adequate matrix solvers.
- Configure relevant numerical parameters, e.g. numerical time step size, simulation time, write precision etc..
- Define suitable sample sets and probe points in the mesh for analysis.
- Parallelize the calculation.
- Take care of numerical stability parameters, e.g. Courant number.
- Control during simulation run time.
- Calculate additional physical quantities, e.g. vorticity, etc.

POST-PROCESSING:

- Visualize the simulation.
- Analysis.

For more detailed information the reader is referred to the author’s Ph.D. thesis [4]. The numerical simulations presented here were realized by using parts of the C++ toolbox OpenFoam-3.0.0 [5]. The libraries include customized numerical solvers as well as pre- and post-processing utilities for the solution of problems in continuum mechanics, including computational fluid dynamics (CFD) and computational aeroacoustics (CAA). The code is released as free and open source software under the GNU General Public License. General aspects about pre-processing, run and post-processing are documented in the OpenFOAM User Guide as well as in the OpenFOAM Programmer Guide [5].

2.2. RESULTS

The stopped wooden organ pipe that was modelled, was produced and provided by the German organ builder Alexander Schuke Orgelbau GmbH [6]. The geometry of the organ pipe and its surrounding area was transferred into a structured 2D computational grid. The mesh size (length × width × depth) is (260 mm × 180 mm × 1mm) with 254342 mesh points, 505170 faces and 126000 hexahedra.

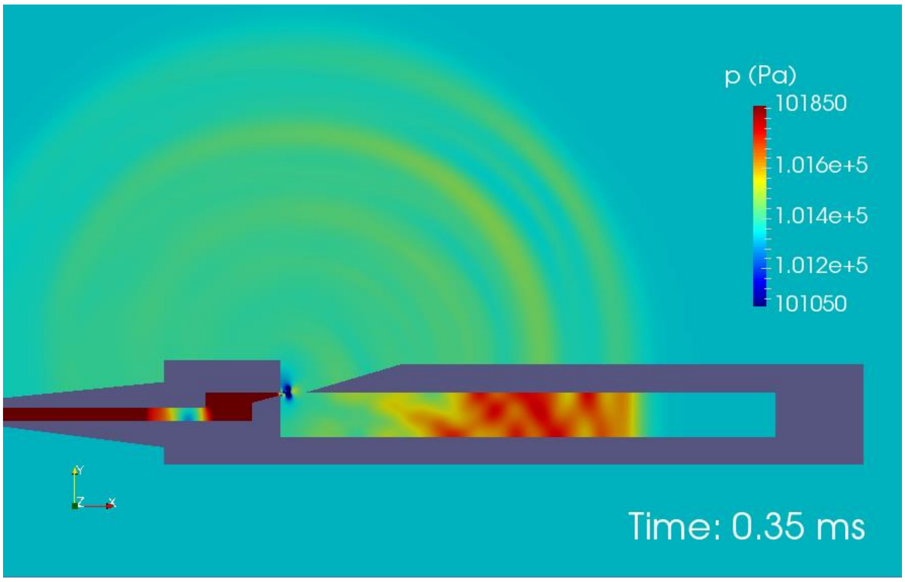

Figure 4 *Snapshot of the numerical simulation of the inital transient of the organ pipe.*

The calculations produce an amount of data of ca. 500 GB. The data contain the field informations of the calculated physical quantities, pressure, velocity, density, temperature, turbulent kinetic energy, vorticity, etc, at each time step. Figure 4 shows a snapshot of the numerical simulation of the initial transient of the organ pipe.

The focus of the analysis is on the propagation of the initial pressure wave fronts in the resonator.

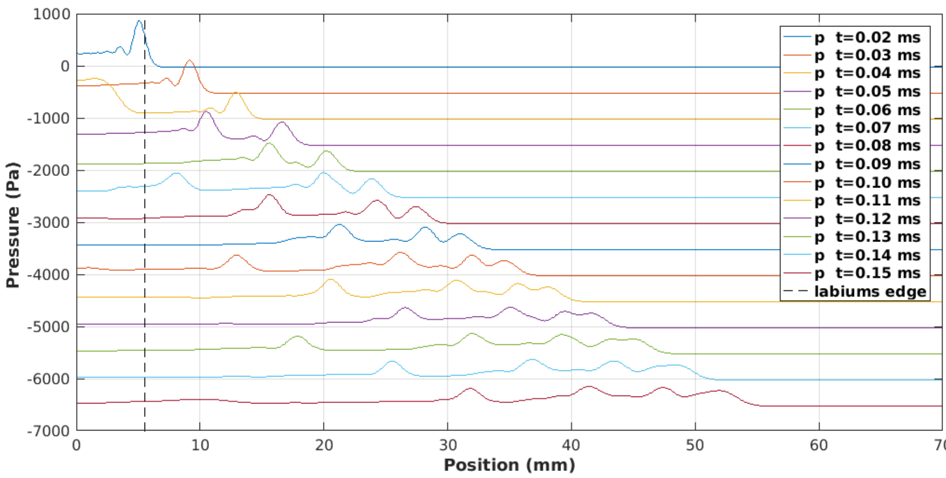

Figure 5 *Propagation of the initial pressure wave fronts in the resonator of the organ pipe.*

Data of the physical quantity Pressure of the cross-section along the resonator length were sampled. In Figure 5 the data are depicted for the first 15 milliseconds. One can see the propagation of the initial pressure wave front along the resonator length.

The Analysis of the data of the pressure at the cross-section in the resonator is shown in Figure 7.Depicted is the propagation of the first three wave fronts f1, f2, and f3, the initial pressure wave fronts which propagate in the resonator of the simulated organ pipe in the initial transient. Marked by red circles is the propagation of the maximum of the primary pressure wave front along the cross-section of the resonator. The red line fits the data. The slope gives the velocity of the peak of the primary pressure wave front which is c_f1 = 363 m/s. Labelled by black circles are the data of the second pressure wave front. Its linear fit gives c_f2 = 408 m/s. Not taken into account are the data points at the very beginning, where the velocity development is nonlinear. The data of the third pressure wave front are labeled green. The fit of the data gives c_f3 = 457 m/s. The circles and curves marked by the blue and the pink lines are the differences between the velocities of the secondary and the velocity of the primary wave front’s maxima. In fact the secondary pressure wave front as well as the third one get damped in a nonlinear way relative to the primary one, but they are still fast enough to accumulate and rebuild the primary pressure wave front.

More results of the study, e.g. the discussion of nonlinear damping of the initial pressure wave fronts and their contribution to the sound generation mechanism in the resonator are subject of current research.

SUMMARY

In the first part of the work acoustic measurements of the initial transient of the trumpet and the recorder are presented. The measurements were realized with a microphone array. The analysis show that in the initial transient pressure waves can be observed that propagate with slightly higher velocities that the local speed of sound. This indicates that these waves have shock wave characteristics.

In the second part the numerical simulation of the initial transient of a wooden stopped organ pipe is discussed. General annotations on implementation and run of complex numerical simulations of aeroacoustical problems were pointed out.
With advanced visualization techniques the complex dynamics of the initial transient process in the resonator were discovered. The analysis of sampled data at cross-section along the resonator show the occurrence of pressure wave fronts that have shock wave characteristics.

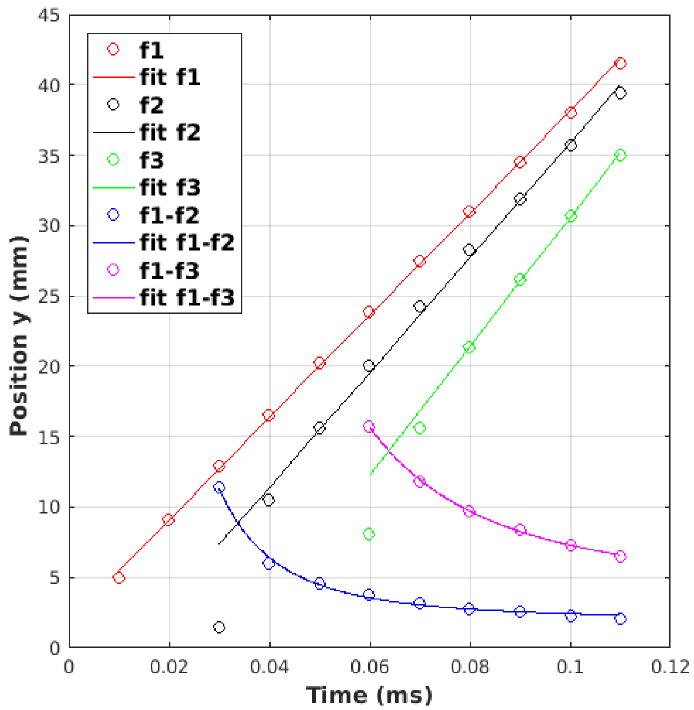

Figure 6: *Data from the numerical simulation. Depicted are the velocities of the peaks of the initial pressure wave fronts which propagate in the resonator of the simulated organ pipe in the initial transient.*

The presented results may contribute to an deeper understanding of the underlying based physical principles of the mechanisms of sound generation of wind instruments in the initial transient.

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