Development of an adjustable pipe-foot model of a labial organ pipe

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In order to investigate the physical processes involved in the build-up of the sound signal in a labial organ pipe a pipe foot model has been developed. The main important parameters, such as positions of the lower and upper labium, the wind pressure in the foot and the width of the flue can be adjusted by means of this model. Moreover, different types of languid and pipe bodies (resonators) can be attached to the model. For the reason of corresponding to a real metal organ pipe these parts of the model are made of "organ metal". The reproducibility of measurements is provided by the micrometer screws applied for the adjustments.

Flow and edge tone measurements were carried out with the help of this model. A comparison with real organ pipes gives some indications for the range of the parameters. Because of the flexible adjustments and the large range of values of every parameter, it is possible to find different ranges with varying parameter settings for the occurrence of the edge tone. The analysis of these measurement results shows the dependency of the edge tone of the adjusted parameters.

1   Introduction

When a jet leaves a flue and impinges against an edge a tone is generated. This phenomenon called edge tone influences the attack transient of the sound of a flue organ pipe. To carry out acoustical investigations on the sound generation of an organ pipe a veridical pipe foot (edge tone) model was developed with precisely adjustable parameters.

Many studies have been published on the edge tone. The most important ones were carried out by Jones [1], Brown [2], Powell [3] et al. The applied edge tone models have worked very well for basic edge tone investigations, however, they have not been suitable for modelling the sound generation in organ pipes.

Pitsch [4, 5] has built an edge tone model on the basis of a diapason 8' C pipe. He has performed several acoustical measurements and flow visualization experiments in a 2-dimensional pipe foot model in a flat-water channel. The main disadvantage of his model was the low reproducibility of the adjustable parameters.

The new edge tone model and the flow and acoustic measurements performed by means of the model are described and discussed in this paper. A thorough study of the behaviour of the edge tone and the resonator measurements will be published later.

2   Edge tone model

A sketch of a typical labial organ pipe is shown in Fig. 1. If the resonator is omitted the remaining part may be regarded as an edge tone model (this corresponds to the right side of the dashed line). Most of the past researches have dealt with completely different edge tone models which are not similar to real labial organ pipes. For example they offer a symmetrical alignment of the (in most cases symmetrical) languid, a very long air channel from which the jet leaves, untypical geometries (flue width, cut up height, body of the languid), too high or too low air pressures and last but not least different kinds of materials but not "organ metal".

Hence an edge tone model with following demands has been developed:
- The dimensions should be consistent with a diapason 8' C pipe.
- Different kinds of languid and resonators can be attached to the model.
- The positions of the upper and the lower labium and of the languid can be adjusted in 0.05 mm steps.

- The angle of the upper labium can be changed.
- Possibility of variable pressure adjustments (pressure measurement inside the pipe foot).
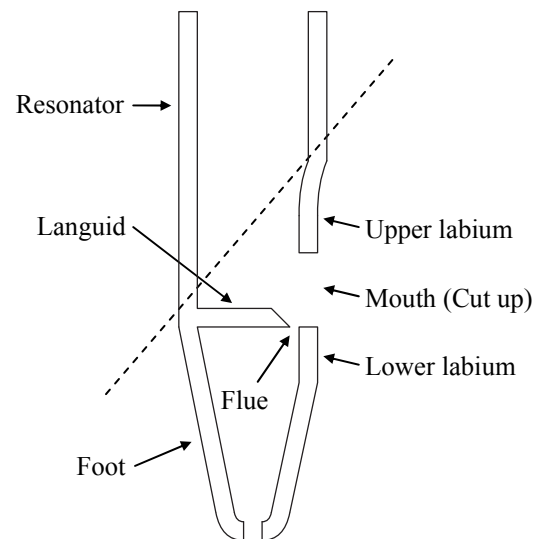- The most important feature: reproducibility of the measurements.

Fig. 1 Sketch of a labial organ pipe

This new edge tone model is shown in Fig. 2. The whole pipe foot was made of aluminium except the languid. To allow for a better rigidity the base plate of the languid was made of steel. The least step size of the micrometer screws (four linear translation stages and one rotation table) is 1 µm. The measurements were done with a lower resolution because of the used "organ metal". "Organ metal" is a quite soft alloy made up of lead, tin, zinc (copper, brass). Compared to aluminium or steel it cannot be machined to a very high accuracy. Therefore, step sizes under 0.05 mm or 0.1 mm make no sense.

The lower labium was attached to a linear translation stage with an adjustment range of 10 mm and adapted into a channel to allow a perpendicular alignment of the edge corresponding to the languid. Two linear translation stages allow a travel range of nearly 100 mm for the upper labium. Additionally, a rotation table was added to allow different angle settings. In order to avoid deflections, the upper labium was attached to an aluminium plate. As mentioned above the base plate of the languid was made out of steel with 2 mm thickness. Different kinds of organ metal languid profiles (edge angles of 45°, 60° and some special designs) can be mounted on the base plate without deformation.

The whole edge tone model was installed on an aluminium rack. The possibility of attaching a resonator onto the model is not shown in Fig. 2 and not discussed in this paper. In Fig. 3 all possible adjustments of upper and lower labium and the languid are shown.
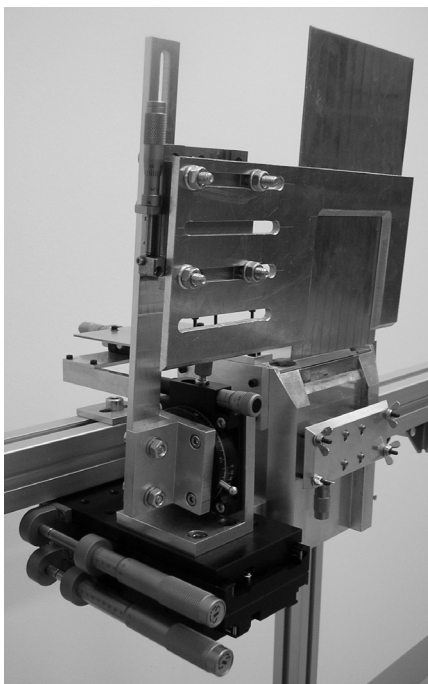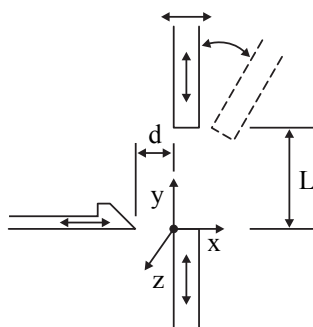

Fig. 2 A photo of edge tone model

Fig. 3 Adjustment possibilities

The origin of the coordinate system is defined as the intersection of the plane of the bottom of the languid, the plane of the inner surface of the lower labium and the vertical plane through the center of the flue. If all parameters are equal to zero, theoretically no jet can be emitted.

3   Experimental system

A blower, a diaphragm bellows and a small slider chest represented the organ instrument. The edge tone model was placed on the slider chest. The pressure in the foot and thus the flue velocity could be adjusted either by changing the weight on the diaphragm bellows or by regulating the speed of the blower. All measurements have been carried out in an anechoic room. A schematic experimental configuration is shown in Fig. 4.

Sound was measured by a B&K 4165 condenser microphone placed horizontally at a distance of 50 mm in front of the lower labium (underside of the microphone and upper side of the lower labium were on the same height), to avoid unwanted blowing noise. Velocity measurements were done by an Airflow TA-5 and a SVMtec hot wire anemometer (3D-Flow-4CTA with 10 μm sensor [9]).
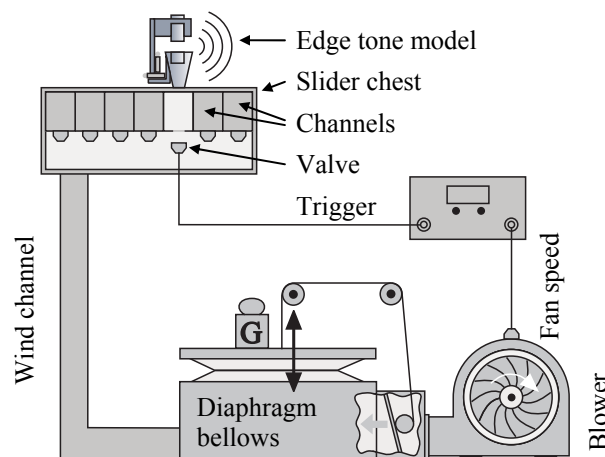

Fig. 4 Measurement setup

By means of a 0.4 mm hole in the back side of the model the pressure inside the pipe foot could be measured with a PT 1000 sensor. For averaging and checking results a HP 35670A Dynamic Signal Analyzer was used.

4   Results and discussion

4.1   Jet velocity measurements

To determine the velocity profile of the undisturbed jet velocity measurements have been performed by using the edge tone model without the upper labium (c.f. Fig. 3). The flue width was changed in 0.2 mm steps from 0.5 mm to 2.1 mm corresponding to the values used in real organ pipes. All measurements were done with a constant pressure of 700 Pa (± 2Pa). By means of the anemometer, placed at a constant distance of 45 mm from the origin, velocity profiles shown in Fig. 5 were measured for each languid position within an angle range 0° to 45°.
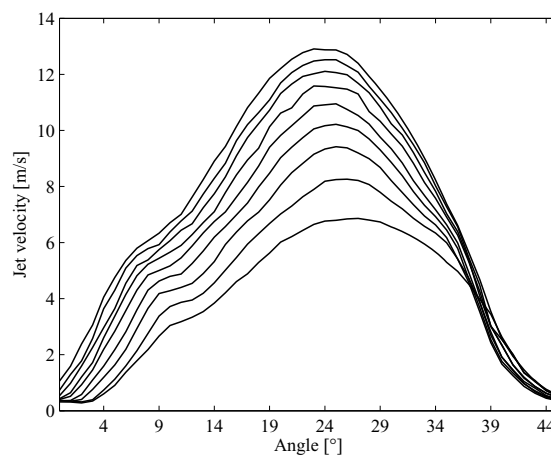

Fig. 5 Velocity profiles at different flue widths

A possible reason for the bumps on the left side of the velocity curves may be the asymmetry of the flue exit. The vortex shedding at the slope of the languid may cause a velocity component which increases the velocity and vanishes with rising angle. Compared to other edge tone models this model offers a very short flue channel. So the resulting velocity profile does not comply with a parabolic or a top hat profile. The angle values at the maximal velocities agree with previous results [4].

Jet velocities at different positions across the flue of 1.1 mm width were measured by the 10 µm sensor. It was placed less than 1 mm above the origin. Because of the symmetry of the edge tone model along the x-axis a symmetric velocity profile was assumed along the flue. Two measurements at the half ($z = 30$ mm, solid line in Fig. 6) and the quarter ($z = 15$ mm, dashed line) of the flue length have been carried out. As shown in the diagram the assumption of symmetry is true. Only slight discrepancies occur between the two velocity profiles. This may be an effect of surface imperfections of the languid and the lower labium. Minor pressure fluctuations also may have an effect on the velocity.
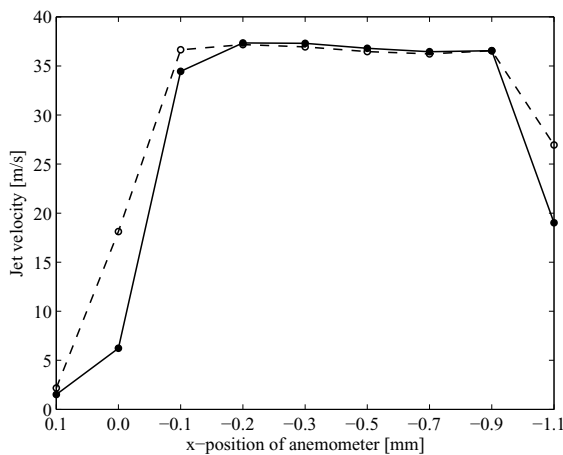

Fig. 6 Velocity profile alongside the flue breadth

The jet velocity calculated with Bernoulli's equation

$$u = \sqrt{\frac{2p}{\rho}} = 34{,}16 \, [m/s] \qquad (1)$$

yields a smaller result than the measured ones. The difference of measured and calculated velocity is caused by the angle of the anemometer. As described it was placed as close as possible to the flue but positioning it horizontally without an angle was not feasible, hence a cosine-component of the transversal velocity is added to the results. The very close positioning causes independency of the velocity profile of the used languids. Different vortex shedding of the languid can be neglected. Ideally both measured velocities should comply with each other.

4.2 Edge tone measurements and frequency analysis

In several earlier published papers ([3], [11], [10], [12]) the existence of so-called edge tone stages or modes had been observed. A gradual change of either the wind pressure or the distance from orifice to edge gives rise to several stages

of edge tone. The pitch of the edge tone changes gradually within one stage, then it jumps suddenly to another pitch corresponding to the next stage. Furthermore a hysteresis was observed by increasing and decreasing the parameter. Jones described the existence of two types of edge tones: one with jumps and one at higher pressures, without jumps.

For edge tone measurements the upper labium was added to the model. The significant parameters are the flue width d (jet thickness), the orifice to edge distance L (cut up) and the jet velocity u. The pressure was held constant at 700 Pa or changed in 100 Pa steps from 100 Pa to 1000 Pa. Edge tone stages have been identified as well separated peaks in the edge tone spectrum. Measured edge tone frequencies (expressed in Strouhal numbers) are plotted in Fig. 7 for the first three stages (stage one dots, stage two rectangles and stage three triangles) as functions of L/d. Up to seven or eight stages have been found in these measurements.

However, no frequency jumps had been observed. This means that all stages coexist. The attention of this work is turned to the development of an edge tone model with respect to real organ pipes. Therefore other materials, geometries and parameter settings were used as in the earlier studies.
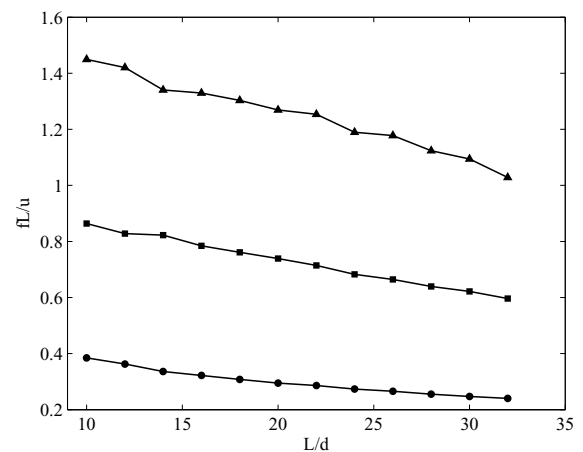

Fig. 7 Edge tone stages (d = 1.1 mm)

An increase of the cut up decreases the frequencies. One possible relationship of the frequency is described in [6] and [13] in terms of the Strouhal number ($St = fL/u$)

$$\frac{fL}{u} = \alpha \sqrt{\frac{d^{n_1}}{L^{n_2}}} \qquad (2)$$

In former experiments the exponents n_1 and n_2 were shown to be between 0.5 and 3 depending on the Reynolds number ($Re = ud/v$, where v is the kinematic viscosity of air). Our investigation deals with Reynolds numbers of $682 \leq Re \leq 4782$ (if $d = 0.3 \ldots 2.1$ mm). To apply the frequency dependency (as in Eq.(2)) to our measurements the exponents should satisfy $n_1 = 1$ and $n_2 \leq 3$.

Most of the amplitude responses constantly fall with increasing cut up length. The values of the first and last amplitude differ between 1 dB and 20 dB. At the moment no applicable relation of the amplitude curves has been found. This will be a subject of further research.

When the ratio L/d is fixed Holger [10] and Howe [12] reported nearly constant Strouhal numbers. In Fig. 8 the Strouhal number is presented as a function of the Reynolds

number (the Reynolds number was changed by changing the pressure, so the exit velocity of the jet).
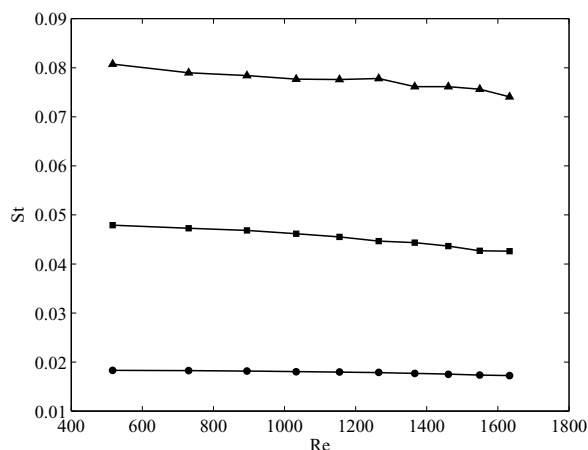

Fig. 8 Strouhal vs. Reynolds number (d = 1.1 mm)

As it is shown the Strouhal number falls linear in each stage. This does not agree with their assumption ($f \sim u$) and results in another exponent n_2. The amplitudes (c.f. Fig. 9) of the first stage rise with increasing Reynolds numbers while those of the second and third stages fall.
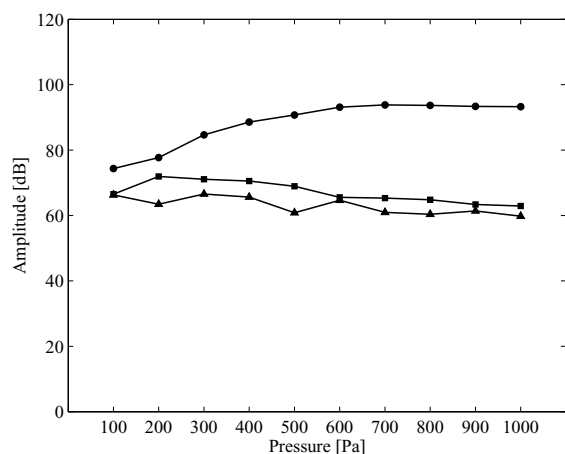

Fig. 9 Amplitude responses

Investigations on the dependency of the frequency on different x-positions of the upper labium had also been performed. The ideal position of the upper labium was defined as the position at which the first stage had the largest amplitude. Variations of the labium positions of ± 0.5 mm did not have any significant influence on the frequency as well as on the amplitude. Both curves were nearly constant.

Other measurements were made with different lower labium positions PosLL = 0.0 … 2.0 mm. Higher lower labium positions had an influence on the emerging jet. The angle between the y-axis and the maximal velocity decreased and so does the ideal position of the upper labium. Only measurements with upper labium positions equal or greater than zero were made. Other cases are not common in organ pipes. The frequencies of all stages linearly rise whereas the amplitudes randomly fall with an unknown function.

5   Conclusion

An experimental study on the edge tone has been conducted. Therefore an edge tone model with adjustable parameters has been developed. The geometries and the used material were based on a real organ pipe. The edge tone model allows reproducible measurements and a high accuracy of the adjustments. Velocity measurements with different flue width showed the angle between the y-axis and the maximal velocity of the emitting jet. These results comply with previous measurements. The frequency results of edge tone measurements already showed differences between previous studies. Main reasons of the different results arise from the used "real" organ pipe parameters for the settings of the edge tone model.

To depict the behaviour of the edge tone further research on the frequency, velocity and especially the amplitude responses are necessary. More detailed results of these measurements will be published in the near future.

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