Measurements on an adjustable pipe foot model

H. J. Außerlechner[1, 2], T. Trommer[1, 2], J. Angster[2, 1], A. Miklós[3]

[1] Universität Stuttgart, Lehrstuhl für Bauphysik, 70569 Stuttgart
[2] Fraunhofer-Institut für Bauphysik, 70569 Stuttgart, Email: hubert.ausserlechner@ibp.fhg.de
[3] Steinbeis Transferzentrum Angewandte Akustik, 70499 Stuttgart, Email: stz746@stw.de

Introduction

When a jet leaves a flue and impinges against an edge a tone is generated. This phenomenon called edge tone mainly influences the attack transient of the sound of a flue organ pipe. A small change of the flue parameters (c.f. Figure 2), such as positions of the lower and upper lip, the width of the flue and the wind pressure in the pipe foot, mostly results in big differences in the build-up and the spectra of the edge tone and the pipe sound.

Many studies have been published on the edge tone. The most important ones are carried out by Brown [1], Powell [2], Holger [3], Coltman [4], Crighton [5] 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.

In order to understand the basic physical processes of the sound generation of an organ pipe a pipe foot model of a labial organ pipe with precisely adjustable parameters has been developed. Furthermore, different types of languids and resonators (pipe bodies) can be attached to the model. Flow velocity, edge tone, mouth tone and pipe sound measurements are carried out with the help of this model. From the results of the measurements, theoretical models have been developed for flow velocity, velocity distribution and edge tone frequencies and for the ratios of the frequencies of edge tone modes. These models may facilitate the design and scaling of flue organ pipes.

Edge tone model

A typical organ pipe consists of two parts: the pipe foot (the lower part) and the resonator (the long tube) attached to the pipe foot. The hole at the front side is called mouth or cut-up (L [mm]) and is defined by the lower lip and the upper lip. The slit between the lower lip and the languid is called flue (d [mm]). If the resonator is omitted the remaining part may be regarded as a pipe foot model.

Most of the past researches have dealt with completely different pipe foot models (in their cases named 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.

Hence a pipe foot model with following demands has been developed:

- The dimensions should be consistent with a diapason 4' C pipe.

- Due to the similarity to real metal organ pipes the most common alloy used by organ builders (60 % lead, 40 % tin) should be used for the relevant parts: these are the lower and the upper lip, the languid and the resonator.

- Different kinds of languids and resonators can be attached to the model. This means resonators with different lengths and or diameters and languids with different languid angles and counter phases. These results are not discussed in the current paper.

- For high reproducibility of the measurements the positions of the lips and the languid can be adjusted with micrometer screws. Moreover, the angle of the upper lip is changeable.

- The pressure in the pipe foot (p_{pf} [Pa]**)** can be measured (by a 0.4 mm hole at the opposite side of the lower lip and very close to the plate of the languid).

A photo of the pipe foot model with these demands is shown in Figure 1. The whole pipe foot is made of aluminium except the languid and installed on an aluminium rack. To allow for a better rigidity the base plate of the languid is made of steel. The least step size of the micrometer screws (four linear translation stages and one rotation table) is 1 µm. The possibility of attaching a resonator onto the model is not shown in Figure 1 and not discussed in this paper.

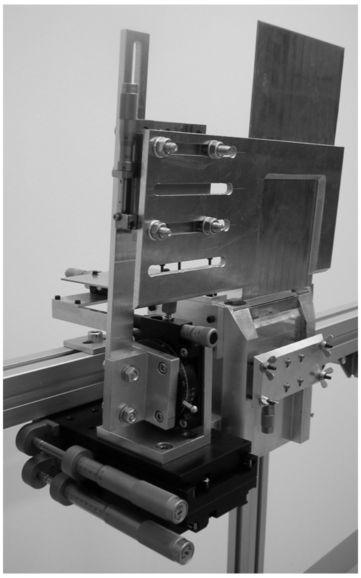

Figure 1: A photo of the edge tone model.

In Figure 2 all possible adjustments of the upper and lower lip and the languid are shown with arrows. 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 lip and the vertical plane of the centerline of the upper lip. If all coordinates are equal to zero, theoretically no jet can be emitted.

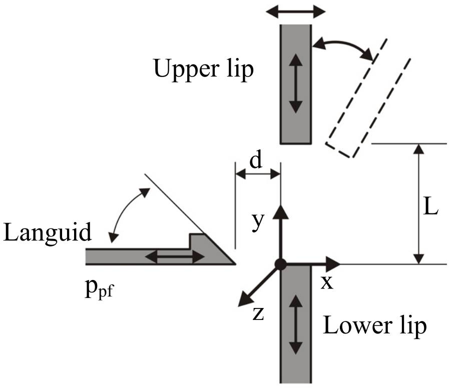

Figure 2: Adjustment possibilities of the edge tone model.

Experimental setup

A blower, a diaphragm bellows and a small slider chest represent the organ instrument. The pipe foot model is placed on the slider chest. The pressure in the foot and thus the flue velocity can be adjusted by changing the weight on the diaphragm bellows. All measurements have been carried out in an anechoic room.

Sound is 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 are done by an Airflow TA-5 and a SVMtec hot wire anemometer (3D-Flow-4CTA with 10 µm sensor [6]). By means of a hole in the slider chest and a hole in the backside of the model, the pressure inside the slider chest and inside pipe foot can be measured with Honeywell 163PC01D36 sensors. For averaging and checking results, a HP 35670A Dynamic Signal Analyzer was used.

Results and Discussion

Jet velocity measurements

To determine the velocity profile of the undisturbed jet velocity measurements have been performed by using the pipe foot model without the upper labium (c.f. Figure 2). All velocity measurements are done with a constant pressure in the pipe foot of 700 Pa (± 2Pa) and a languid angle of 45°.

In Figure 3 the velocity profiles at five different flue widths are shown. Ideally, top hat profiles are expected. Due to the boundary layers of finite thickness so-called Nolle velocity profiles [7] result at the flue. The jet velocity calculated with Bernoulli's equation (1) is 34.16 m/s and gives an approximation of the expected exit velocity ($\rho_{air} = 1.2$ [kg/m^3]).

$$U_{0B} = \left(2p_{pf}/\rho\right)^{1/2} \qquad \text{[m/s]} \qquad (1)$$

The average velocities at the flue (calculated at the area of nearly constant velocity) are slightly greater than U_{0B}. Because of the vena contracta effect [8] the jet velocity increases at this region. Furthermore, the entrainment effect [9] causes inflow at the boundaries of the jet. The jet draws air into itself and so the velocity increases at the boundaries too.

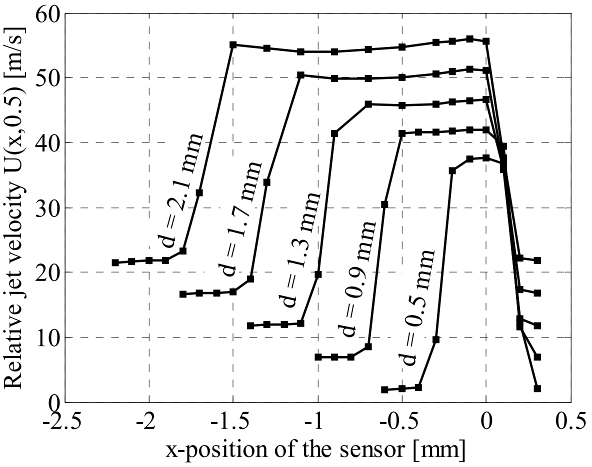

Figure 3: Jet velocity profiles at the flue at different flue widths (y-position of the sensor ≈ 0.5 mm). The profiles except the profile at d=0.5 mm are shifted: d=0.9 mm: +5 [m/s], d=1.3 mm: +10 [m/s], d=1.7 mm: +15 [m/s] and d=2.1 mm: + 20 [m/s]. The symbols denote the measured data points.

The Gaussian distribution of equation (2) gives the best fits of the velocity profiles measured at different y-positions of the sensor of the anemometer. The parameters are the offset u_0, the $1/e$ width $w(y)$, the area $A(y)$ and the center $x_c(y)$ of the distribution.

$$U(x,y) = u_0 + \left(\frac{A(y)}{w(y)(\pi/2)^{1/2}}\right) \exp\left(-2\left(\frac{x-x_c(y)}{w(y)}\right)^2\right) \qquad \text{[m/s]} \qquad (2)$$

The x-position of the centerline velocity $U(x_c, y)$ dependent on the y-position of the sensor is shown in Figure 4. From these data, the jet exit angle can be calculated. Its value is about 25°. The deflection of the jet agrees well with the data found by Yoshikawa [10].

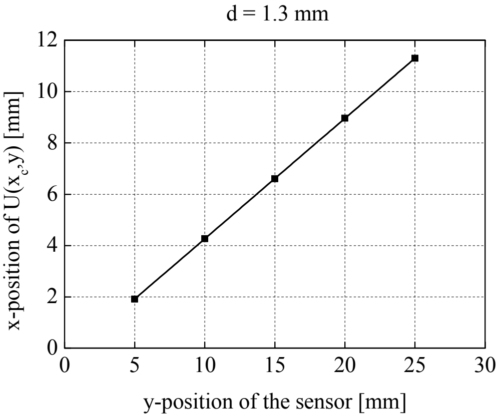

Figure 4: Dependency of the x-position of the centerline velocity $U(x_c, y)$ on the y-position of the sensor ($d = 1.3$ mm, $p_{pf} = 700$ Pa).

In addition to the exit angle a power function dependency of the centerline velocity on the y-position is found. It decreases with $y^{-1/2}$.

Edge tone measurements and frequency analysis

An edge tone spectra normally offers one dominant frequency and some higher frequency components (modes). The bandwidth, the width between the modes and the amplitudes of the modes depend on the adjusted parameters. For acoustical measurements the x-position of the upper lip is adjusted so that the amplitude of the first edge tone mode is the highest (c.f. Figure 5). Again, an angle can be calculated. This value correlate well with the angle calculated from the velocity measurements. Thus, it is shown that the maximum amplitude of the edge tone is generated at the maximum of the velocity profile; at the centerline velocity.

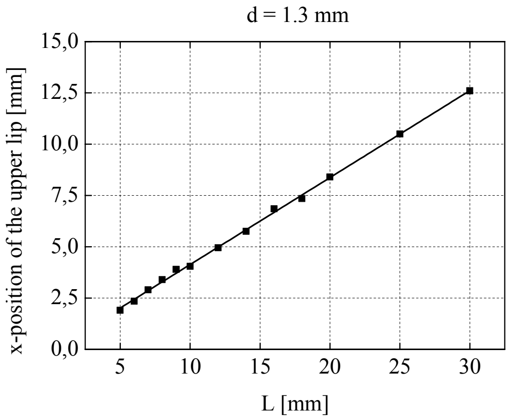

Figure 5: Dependency of the x-position of the upper lip on the cut-up ($d = 1.3$ mm, $p_{pf} = 700$ Pa).

In Figure 6 the first three edge tone modes dependent on the pressure in the pipe foot are shown. If the pressure is increased the frequencies also increases, but with different slopes. Further, it can be seen that the edge tone modes coexist. In several mentioned literature the authors say that increasing and decreasing the pressure cause a hysteresis phenomenon of the amplitude of several edge tone modes. This effect is not found and approved with these measurements.

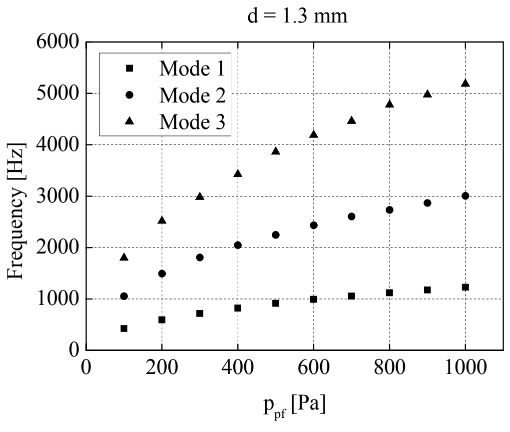

Figure 6: First three edge tone frequency modes dependent on the pressure in the pipe foot p_{pf} ($d = 1.3$ mm, L=10 mm).

The edge tone frequencies are also dependent on the cut-up and can be calculated in two ways:

a) The Strouhal number is set constant. Therefore, the frequency can be calculated as the velocity at the flue $U(x_c, 0)$ divided by the cut-up L and multiplied by a velocity correction factor expressed in terms of the flue width d and the cut-up L (see equation (3); parameters: mode number N, fit parameters $C_{d,N}$, $n_{d,N}$).

$$f_{a,N} = U(x_c,0)\underbrace{C_{d,N}\frac{d^{1/2}}{L^{n_{d,N}}}}_{\text{correction factor}} \qquad [\text{Hz}] \qquad (3)$$

b) The second approach deals with the assumption of a feedback loop (see equation (4)). The emitted jet needs a travel time τ_1 from the flue to the upper lip. The acoustic signal generated at a little distance downstream the tip of the edge of the upper lip has travel time τ_2 back to the flue (velocity of air c_0 in [m/s], position of the dipole source on the upper lip $\triangle L$ [mm]).

$$f_{b,N} = \frac{1}{\tau_1 + \tau_2} = \frac{1}{\int_0^{L+\triangle L} \frac{dy}{u(x_c,0)} + \frac{L+\triangle L}{c_0}} \qquad [\text{Hz}] \qquad (4)$$

Two different aspects of the exponent n exist: in Holger [3] n is set to $3/2$, in Bamberger [11] and Paál [12] $n = 1$. Comparing the calculated frequencies of equation (3) and (4) with the measured ones show, that both models do not give good results for the frequency modes (see Figure 7: $f_{a,1}$ dashed dotted line and $f_{b,1}$ dashed line). If formula (3) is modified ($n \approx 1.3$) the calculation correlates well with the measured data (see Figure 7 solid line). Calculations with equation (4) gives again better results especially for higher frequency modes.

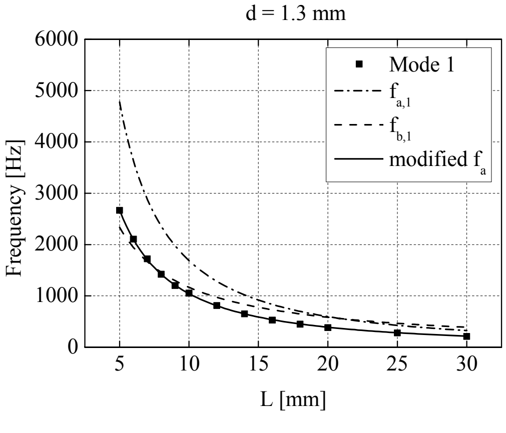

Figure 7: Measured mode one edge tone frequencies dependent on the cut-up and compared to different calculation models ($d = 1.3$ mm, $p_{pf} = 700$ Pa).

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 are based on real metal organ pipes. The edge tone model allows reproducible measurements and a high accuracy of the adjustments.

Velocity measurements at different distances to the flue showed the angle between the y-axis and the maximal velocity of the emitting jet. These results comply with previous measurements.

By acoustical measurements, it is found that the maximal mode one edge tone amplitude is generated at the maximal jet exit velocity. 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.

Acknowledgement

The authors acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG: „Development of a physical model for computer simulated production of the sound of a labial organ pipe“, Sb SE 1561/1-1).

References

[1] G.B. Brown, “The vortex motion causing edge tones”, Proc. Phys. (London) 47, 703 (1937)

[2] A. Powell, “On the edgetone”, J. Acoust. Soc. Am., Vol. 33, No. 4, April, 395-409 (1961)

[3] D.K. Holger, “Fluid mechanics of the edgetone”, J. Acoust. Soc. Am., Vol. **62**, No. 5, pp. 1116-1128 November (1977)

[4] John W. Coltman, “Jet drive mechanisms in edge tones and organ pipes”, J. Acoust. Soc. Am., Vol. **60**, No. 3, September (1976)

[5] D. G. Crighton, “The jet edge-tone feedback cycle; linear theory for the operating stages”, J. Fluid Mech., Vol. 234, pp. 361-391 (1992)

[6] Reference to the SVMtec GmbH. URL: `http://www.svm-tec.de`

[7] A. W. Nolle, “Sinuous instability of a planar air jet: Propagation parameters and acoustic excitation”, J. Acoust. Soc. Am., Vol. **103**, No. 6, pp. 3690-3705 June (1998)

[8] Y. A. Cengel, J. M. Cimbala, “Fluid Mechanics – Fundamentals and Applications (In SI Units)”, ISBN-13: 978-0-07-061197-9, Tata McGraw-Hill Edition, 2006

[9] D. J. Tritton, “Physical fluid dynamics”, ISBN: 0-442-30131-6 cloth, Van Nostrand Reinhold, 1977

[10] S. Yoshikawa, K. Arimoto, “Measurement of velocity profiles of the jets issuing from some flue geometries typical of air-jet instruments”, ICA 2001, Rome, 2 pages in CD-Rom Vol. **4**

[11] A. Bamberger, E. Bänsch, K.G. Siebert, “Experimental and numerical investigation of edge tones”, Z. Angew. Math. Mech., **84**, pp. 632-646 (2004)

[12] G. Paál, I. Vaik, “Unsteady phenomena in the edge tone”, International Journal of Heat and Fluid Flow, **28**, pp. 575-586 (2007)