Proceedings of the International Symposium on Musical Acoustics, March 31st to April 3rd 2004 (ISMA2004), Nara, Japan

Operation of Flutes at Low Pitch Investigated with PIV

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Abstract

The operation of flute at low pitch is investigated with Particle Image Velocimetry (PIV). The dependence of the sound quality and stability of operation as a function of the span wise dimension of the flue is determined. The flue of 9.5 mm width, which is normally used for higher pitch, is replaced by a wider one of 12.5 mm width. The operation with the wide flue improves the stability against over-blowing. The following results can be deduced from this investigation at a given blowing pressure: (1) The pressure amplitude in the resonator is increased by 20%, (2) the frequency spectrum has a higher fundamental. In order to understand the underlying mechanism the PIV records the jet movement in the transverse and span wise dimension. The larger flue exhibits a span wise modulation of the jet not only in amplitude, but also in phase. It is argued that the change of the standoff of the labium from the flue exit due to the oval hole of the embouchure creates a stabilizing effect against over-blowing.

1. Introduction

It is known from experience that for Boehm flutes the low pitch requires special attention when jumping from mid range pitch to 262 - 330 Hz. Apart of the correct blowing pressure the span wise dimension of the opening of the lips plays a dominant role. The complete coverage of the labium with the jet seems to be important. In this investigation a possible clue for this sensitivity is searched for. Keeping most parameters as blowing pressure and geometrical distances unchanged the span wise dimension of the flue is increased and the resulting effects are observed. The PIV is specially suitable for such an investigation, since it is able to record jet speeds as well as acoustical velocities in the field of investigation, which contains the sources terms of the acoustical power.

2. Experimental setup

In this investigation the flute is operated through an artificial mouth formed of silicon cautchouc with a flue inserted between the lips. The opening is chosen for normal operation at higher pitch to be 0.9 $\times$ 9.5 mm^2 in height

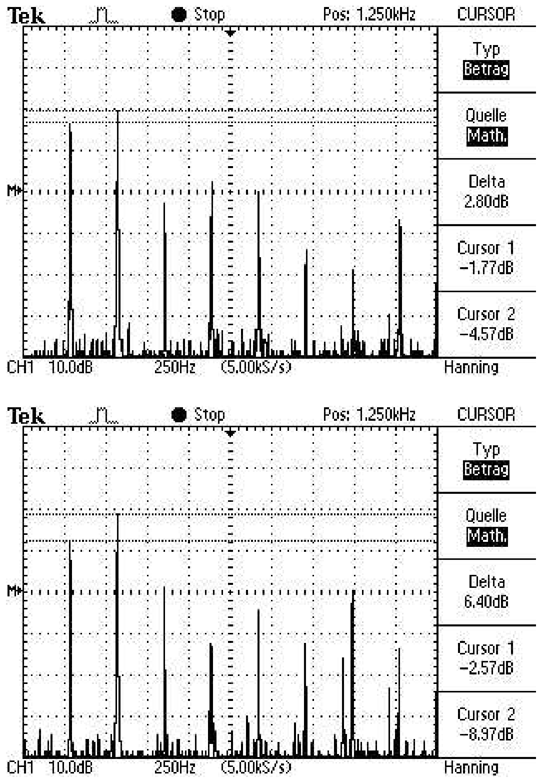

Figure 1: Spectral distribution of the pressure amplitude: above 12.5 mm flue, below: 9.5 mm flue.

and the span wise dimension, later referred to as 'narrow flue'. For this investigation the flue was replaced by a wider one with 0.74 $\times$ 12.5 mm^2 in opening, the 'wide flue'. This size covers the hole of the embouchure completely. The fingering corresponds to D_4 at a frequency of about 290 Hz. Compressed air is loaded with $\sim$10 μm diameter droplets for the visualization.

The PIV system is composed of a twin head NdYAG laser, a double exposure video camera and a timing control. The camera view catches the region between the flue exit and the labium. For the span wise investigation data are taken at several positions in 2 mm span wise steps. This direction is referred to as the Z-axis, pointing to the foot of the flute. In a special setup the camera also took the view from above onto the embouchure in order to record a possible span wise modulation. A reference microphone, which is inserted into the flute body at the G# key position, serves as pressure measurement and as a trigger near the zero crossing.

3. Data taking

Typically the data acquisition is done at 10 phases per period. Each set consists of several shots which are averaged later. The cross correlation is evaluated in half overlapping pixel areas corresponding to an interrogation area of 0.144×0.144 mm^2 for the side view of the jet and fourfold in area for the top view. The spectra of the pressure microphone are taken for the two types of the flue, seen in Fig. 1. It is observed that the ratio for the fundamental to the first harmonic is increasing as the wide flue is used.

Typical values for the operation of the flute, the results concerning the jet movement and the spectra are given in Table 1. Here the jet speed is U_{jet} is kept the same, and the effective pressure amplitude of the resonator A_{res}^{eff} improves in case of the wide flue.

Table 1: Values and results for the operation of the flute at 290 Hz.

Type of flue	12.5×0.74	9.5×0.9	mm^2
$U_{jet_{max}}$	20.0	21.0	m/s
A_{res}^{eff}	80	63	Pa
A_{f_0}/A_{f_1}	-2.8	-6.4	dB
Eff. span width	10.0	6.0	mm
Jet ampl., RMS	0.77	0.58	mm
Jet ampl., peak-peak	2.0	2.0	mm
$\Delta\Phi_{min}$	30	5	°

4. PIV data evaluation

The PIV data was taken with a vertical light sheet in steps of 2 mm along the axis of the flute. Representative examples are displayed in Fig. 2. The labium of the flute, the lips and the flue is indicated. Also fringe fields have been recorded in order to verify the actual extension of the jet. The data displayed is taken for the phase of 144° just before the jet moves downwards into the embouchure. In Fig. 3 the RMS of the position amplitude at 5.0 mm distance from the flue exit is displayed as a function of the span wise position. A damping of the amplitudes are seen if the distance from the center of the flue is increased, especially for the narrow flue. Table 1 list the half width of the amplitude as the effective span width.

The velocity field as viewed from above is seen in Fig. 4. The light sheet intersects the investigated volume about 1.2 mm above labium with an angle of about 12°

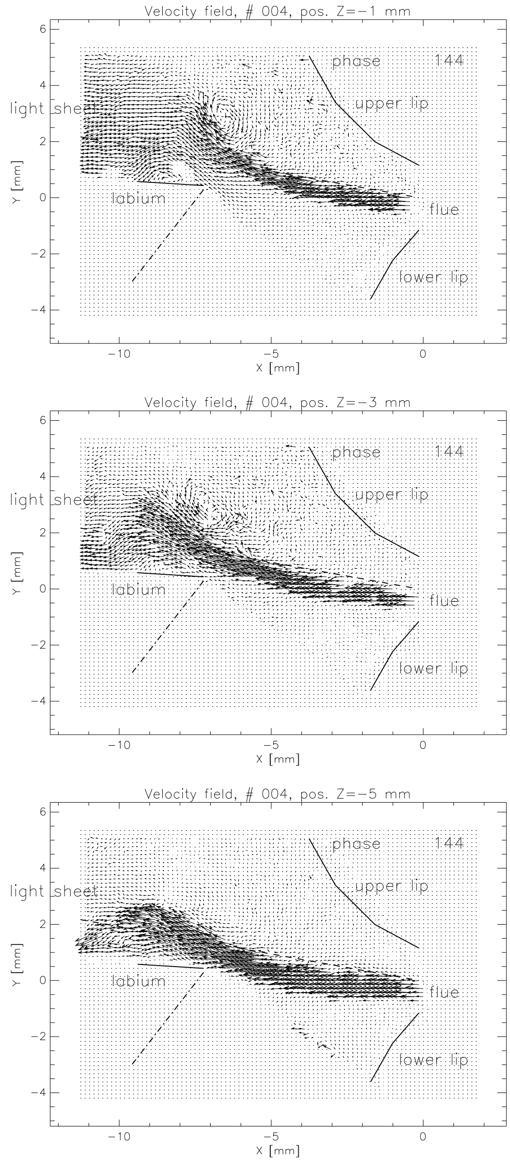

Figure 2: Velocity fields. Top, middle, bottom: at position Z= -1 mm, -3 mm, -5 mm off center, respectively.

with respect to the jet axis as indicated in Fig. 2. The field is strongly changing span wise because of the change of the amplitude as well as the change in phase. The velocity components in Z-direction are small, however.

A more detailed information is obtained from the position as a function of the phase as well as in Z, see Fig. 5. Symmetric Z-positions are averaged. A double peak structure at 130° and 230° with a deep minimum around 200° is typical for the transverse movement of the jet at low pitch: most of the time it is hovering above the labium. More detailed investigations show that with the increase of blowing pressure the secondary minimum near phase 20° would fully develop to the over-blowing condition into the former first harmonic. It is also seen

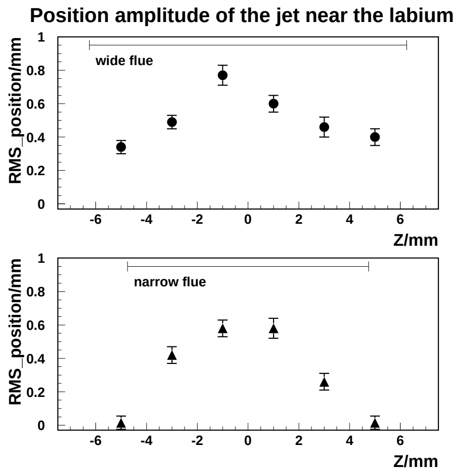

Figure 3: Jet amplitude at 5 mm from the flue exit as a function of Z (geometrical width is indicated).

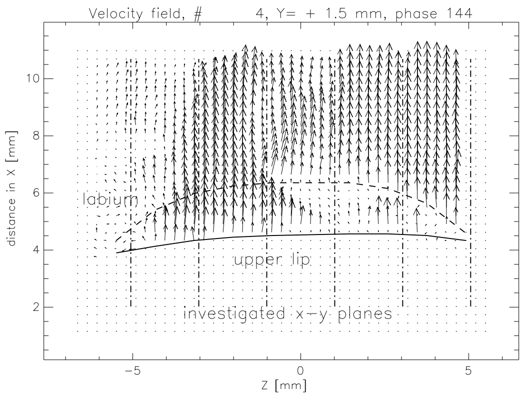

Figure 4: Velocity field of the wide flue viewed from top.

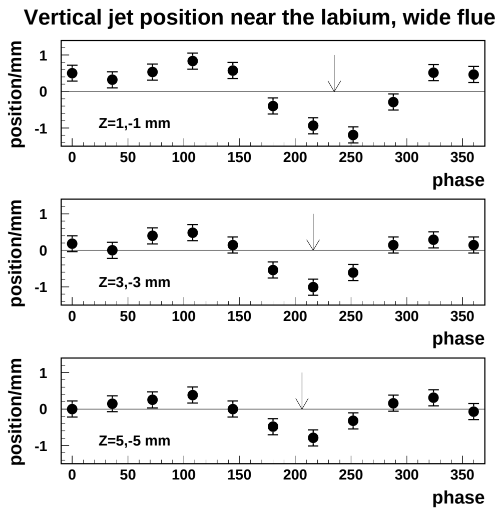

Figure 5: Jet position at 5 mm from the flue exit as a function of the phase for the wide flue.

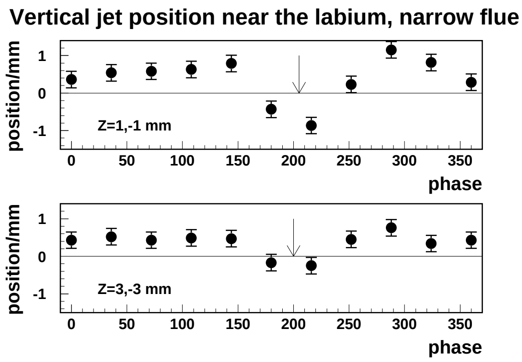

Figure 6: Jet position at 5 mm from the flue exit as a function of the phase for the narrow flue.

that the minimum in amplitude moves in phase by about $\Delta\Phi_{min}$=30° going from the center towards the rim of the flue. For the case of the narrow flue the minimum is more pronounced corresponding to the higher amplitude of the first and higher harmonics, see Fig. 6. Its tendency for over-blowing is closer if the blowing pressure is increased. The phase stays almost constant as a function of Z. These values are also indicated in Tab. 1. It should be mentioned that in this setup the actual over-blowing occurs only at pressures well above 150 Pa for the wide flue. The investigation of the fringe fields beyond ±4 mm in case of the narrow flue does not support an 'acoustical short circuit'. Its size and phase goes conform with the acoustical field being simulated without the jet.

5. Interpretation of the result

The main results are (1) a sizable increase of the effective jet width with the span wise extension of the flue, and (2) a distortion of span wise coherency of the jet due to the phase shift for the wide flue. As can be seen from Fig. 4 the distance between flue exit and labium w changes more than 1.1 mm going from the center to the rim. The Strouhal number $Sr_w = f \cdot w/U_{jet}$ changes by >17%. This results in a broadening of the interaction time of the jet with the labium which is essential for the acoustic source terms. This tends to suppress the higher harmonics which otherwise would lead to the condition of over-blowing. For the span wise narrow jet the Strouhal number stays essentially constant and such an effect would be absent. These findings are supported by the observation reported for organ pipes with slanted cut up which leads to a suppression of the higher harmonics [1].

References

[1] A. Wilson Nolle, "Spontaneous and Induced Span-wise Variability in Self-Excited Air Jet Oscillation", 17th Int. Congress on Acoustics, Rome Sept. 2-7, 2001 Vol. IV