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INVESTIGATION OF JET MOTION IN FLUTES

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ABSTRACT

This investigation intends to measure jet properties in flutes. The classic flute covers more than three octaves by overblowing. Various recipies are described in textbooks in order to facilitate the overblowing, but they are inadequate in terms of the properties of the excitation mechanism. In contrast to flue pipe investigations of organs there are only a few investigations published, let alone examples of jet visualisation. The flow visualisation through "Schlieren"-method was used to search higher modes starting with a flue pipe. A mock-up of the lips of the flute player was constructed and the above method applied to the flute. Some main properties of jet movement can be displayed. For more quantitative investigations the hot wire anamometry (DANTEC C56, 1 micrometer wire diameter, temperature compensated) has been applied. First results of jet velocity profiles and scaling properties in flutes are presented.

1. INTRODUCTION

The investigation of jet driven systems for the production of sound is well understood qualitatively and to some extend also quantitatively. An essential feature is the description of the jet as it develops in space and time. The fact that the jet and the acoustical field is a coupled system complicates the description, however.

The authors of reference [1] have investigated the excitation mechanisms in organ flue pipes and flutes. The basic principle for a stable operation is the fixed ratio of the transit time of a perturbation between the flue exit and the labium to the periode of the fundamental. The author of reference [2] investigates the properties of the jet movement by similar methods as described here. Among other findings the conclusion is derived that the jet response to the pressure gradient of the acoustical field. This seems to be in some discrepancy to the result presented in reference [1].

Additionally there are a number of interesting questions specifically related to the flute.

Along with reference [1] the description the jet can be represented as a travelling wave with an exponentially increasing amplitude. The position of the labium for organ flue pipes is then roughly at $\lambda/4$. For flutes this situation is slightly different. The operation of the flute usually requires a higher blowing pressure than commonly used for organ flue pipes, see reference [1], p. 463.

For flutes the pitch can be changed over more than three octaves. The change of blowing pressure is most obvious. However there are relatively small geometrical adjustments, as for the width W (distance of the flue to the labium) and the height h of the jet which might be understood to some extend theoretically, see also reference [3].

Model calculations up to now do not include parameters being important by experience as the transversal "depth" of the jet d nor the possible turn of the main axis of the transverse shape of the jet with respect to the labium.

This paper tries to adress some of these questions as a preliminary investigation with a "realistic" experimental set-up.

2. EXPERIMENTAL METHODS

The undisturbed observation of the jet dynamics can be achieved by the "Schlieren"-method operating the jet with CO_2. The viability of the method was tested with a organ flue pipe. The dimensions of the jet are W=5 mm, h=1 mm and d=30 mm. The open resonator has a length of 500 mm with a square cross section of 30·30 mm^2. Two optical windows give way to the light path through the jet. The set-up used a high pressure Hg gas discharge as light source and a concave mirror (focal length of 5.500 m, diameter of 28 cm). The observation of jet movements has been recorded with a video camera. A stroboscopic illumination has been used by a rotating disc with holes representing a light shutter of adjustable frequencies up to 1.2 kHz. The flue pipe has been operated also in higher modes than the fundamental. Jet movements and shapes have been recorded. A general observation is that the jet remains laminar in first part of the distance betweeen the flue exit and the labium. The turbulence appears then rather near the labium. As an example in figure 1 a "split" jet is indicated as the jet moves across the labium. The frequency of the light shutter is 284 Hz and equals the frequency of the sound. This may be interpreted as the development into separated vortices. This feature is also seen to some extend in the higher registers.

The jet of a flute has been recorded under similar conditions. A nozzle has been constructed mimicking the flute players lips, see figures 2 and 3. The jet depth d is continuously adjustable and the height h in steps of 0.5 mm. The quality of sound is nearly that of a flute player. The frequency spectrum derived from the set-up resembles that of a "naturally" blown flute.

The quality of the visualisation is worse than that of the organ flue pipe because of the much reduced length the light path traversing the jet. Moreover the embouchure is not transparent, so the observation of the jet is impossible there. Snapshots of the jet movement can be seen in the figures 4 (jet center above the labium) and 5 (jet center below the labium). The frequency corresponds here to 577 Hz. More data is available for 333, 714 and 1315 Hz. As in the case for the organ flue pipe the movement of the jet is similar when the situation at 333 Hz is compared with that at 714 Hz. At the frequency of 1315 Hz the height h was set to 0.5 mm. Here there is a concentric wave pattern starting from the flue and spreads over the jet, which can be seen in figure 6. It is present only in the sounding mode of operation. There

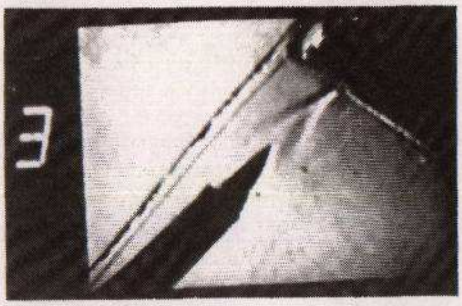

Figure 1: Visualisation of the Jet in an organ flue pipe

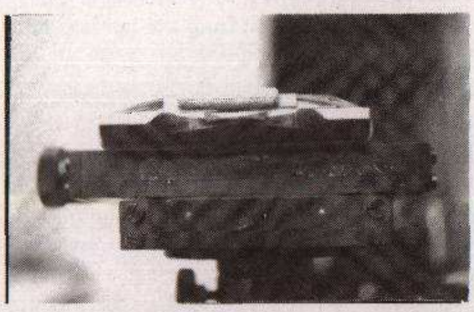

Figure 2: Mock up of flue

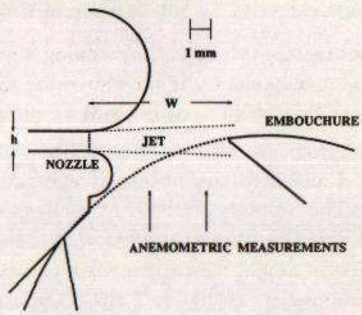

Figure 3: Arrangement for the measurements

Figure 4: Jet above the labium, at 577 Hz

Figure 5: Jet below the labium, at 577 Hz

seems to be a feed back mechanism of the acoustic wave onto the jet at the flue exit. Further investigation would be needed here.

Since video pictures are difficult to be interpreted quantitatively at this level, it was tried to record the movement of the jet with a hot wire anemometer. A similar set-up as shown in above figures has been used. The figure 3 shows also the positions at which the anemometer measured the velocities. The flue exit was set to h=1.0 mm and d=10.0 mm. The flute has been operated with compressed air at nominal frequencies of 330, 660 and 990 Hz. The velocities where measuered in two ways:

- Average velocity: by the reading of the digital volt meter, integration time >1/10 s.
- Instantaneous velocity: The analog signal has been displayed with an oscilloscope. The high fequency cut off is far above the audible range. The transition from the laminar to the turbulent regime could well be observed.

The table 1 displays the obtained average values along with the pressure applied to the "mouth". The velocity derived from Bernoulli's law is given as well. Since the jet sweeps across the wire the time dependence of the signal reflects the oscillating boundary of the jet. The position in height for each setting was adjusted for the maximum peak to peak amplitude of the anemometer. In figure 7 the anemometic measurement of the instantaneous velocity is displayed for a position along the jet at 3 mm together with the pressure signal of an electret microphone being positioned at ~5 cm from the embouchure. The left (right) side corresponds to the measurement below (above) the center of the jet. The maximum velocity

Table 1: Velocity [m/s] and phase of the jet movement with respect to the acoustic pressure at f_{nom}= 330, 660 and 990 Hz

pitch/pos.	$U_{j,Bern}$	$U_{j,ane}$ at 3mm	$U_{j,ane}$ at 6mm	Φ
E_4, above center		8.0	3.8	
E_4, center	15.9	11.5	4.2	87°
E_4, below center		7.0	3.8	
E_5, above center		16.0	5.5	
E_5, center	23.9	20.0	5.7	118°
H_5, below center		12.0	5.5	
H_5, above center		23.0	10.0	
H_5, center	33.8	33.0	12.0	101°
H_5, below center		23.0	10.0	

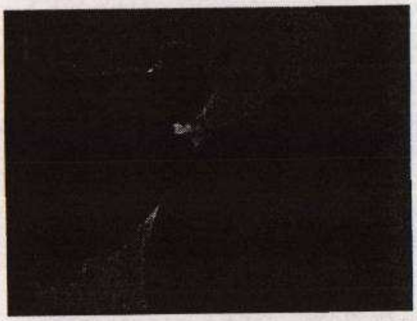

Figure 6: Jet at 1315 Hz, h=0.5 mm, interference structure at the flue

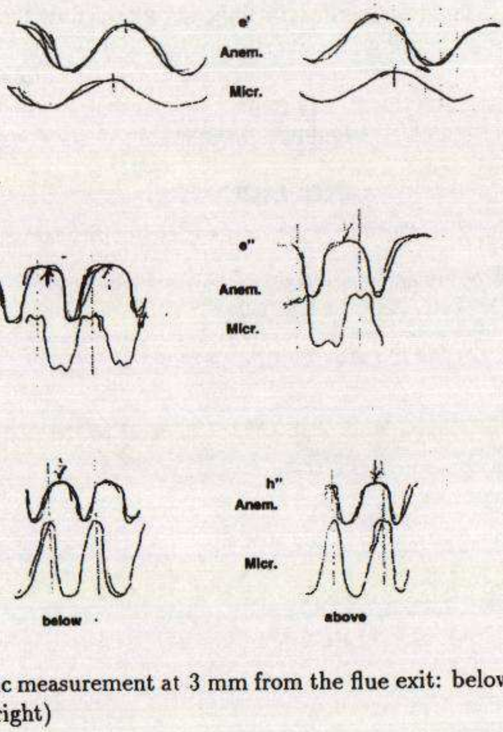

Figure 7: Anemometric measurement at 3 mm from the flue exit: below the center line of the jet (left), and above (right)

is recorded downwards. In order to facilitate the interpretation for the phase jet position the signal of the anemometer on the left side can be taken as the position of the jet in height (up being a position above the labium). The positive pressure signal of the microphone is recorded upwards. As a result there is a phase shift of the jet movement with respect to the acoustical pressure of +90°. The same measurement was performed at a distance of 6 mm from the flue exit. The phase shift (not corrected for the finite distance of the micropone from the embouchure) is deduced from these measurements and given in table 1 in the last column.

3. RESULTS AND CONCLUSION

This investigation was originally initiated to look for higher modes in the jet movement in the flute, in order to verify that the overblowing can be initiated by conditions other than the increase of blowing pressure. Also the tone quality at the high registers was a point of interest. In spite of the increased experimental difficulty for the flute the optical measurements presented here show similar behaviour of the jet movement for the flute as for organ flue pipes. The measurement with the hot wire anemometry yields results of more quantitative nature. Especially the phase of the movement with respect to the acoustical field has been determined and seems to be in agreement of the findings of the author of reference [2].

4. REFERENCES

[1] Fletcher and Rossing, *The Physics of Musical Instruments,* Springer Verlag, 1990

[2] J. W. Coltman, *Jet behavior in the flute,* J. Acoust. Soc. Am. 92(1992)74 and *Time domain simulation of the flute,* Am. 92(1992)69

[3] Sawada and Sakaba, *On the transition between sounding modes of a flute* , J. Acoust. Soc. Am. 76(1980)1790