Vortex sound of flutes observed with Particle Image Velocimetry

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Abstract

It is of fundamental interest to prove the validity of vortex sound source derived from Lighthill's stress tensor for the radiation power in the far field. Based on this theory the vortex source term has been proposed by Powell (1964) and used by Howe (1975). The aim of this investigation is the validation of the vortex source terms using Particle Image Velocimetry (PIV). The flute serves as a good example due to its flexibility in register and dynamics. With the PIV the flow pattern of the jet-edge interaction, and also the acoustic flow is determined. The acoustic velocity at the embouchure field is generated by a speaker system at the foot of the flute. Finally the power density is derived using the vorticity, the jet speed and acoustical velocity field over the whole volume between the flue exit and the labium. The flute is operated at frequencies near 570 and 1140 Hz with various sound power levels between 0.05 to 2.3 mW at each frequency. In an additional investigation the acoustic radiation power is determined at above frequencies and different jet speeds. The following findings are presented:

- The space integrated and time averaged power of the source terms turns out to be positive.
- There is a dominant contribution near the labium.
- The source term power compares well with the measured far field power of the flute for different jet speeds.

1. Introduction

Flue instruments are investigated since quite a time with respect to the sound mechanism. Basically, the jet driving mechanism is thought to be either due to the volume flow model [1] or due the pressure difference across the labium [2]. From Lighthill's tensor the vortex sound can be derived. It is generated when the moving vortex delivers work in a potential of the acoustic field [3] [4]. This is also known as the Magnus effect. In [5] the vortex sound mechanism is investigated in order to understand the energy balance for the operation of recorder-like instruments. Here, the investigation uses the PIV in order to obtain quantitative determination of the vortex sound term. This work is a continuation of the investigations presented in the Forum Acusticum 2002 [6], where the power of an isolated vortex near the labium was determined. The acoustical field needed for the source term is created by an externally excited standing wave in the resonator of the same frequency as the sounding frequency of the flute. In this investigation the volume of integration is extended well into the jet itself. The resulting power is quantitatively compared with the acoustical power at different conditions. The aim is to span a large range in dynamics and different frequencies in order to observe possible limits of the method.

2. Experimental setup

This investigation uses the a similar setup as in [6]. 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 of the flute to be 0.9 mm in height and 9.5 mm in width. Compressed air is loaded with $\sim$10 μm diameter droplets for the visualization. The blowing pressure in the mouth is measured with a pressure gauge.

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 space beyond the labium, in total about 11 mm. Its axis is arranged in such a way that some space below the labium is visible, see Fig. 1.

A reference microphone, which is inserted into the flute body at the 'Gis' key position, serves as a trigger and pressure measurement. The pressure calibration has been performed for reference of the absolute acoustical power. The excitation of the acoustical wave in the resonator is created with a speaker-exponential horn system with a circular ending matching the flute's diameter. The coupling distance was kept $>$22 mm without impedance change of the resonator. The measurement of the acoustical field at frequency 1140 Hz (D_5 fingering) requires a special flute body with circular ending. For the operation at 570 Hz (D_4 fingering) only the foot was replaced by a tube with 50 mm length. A box shaped confinement volume with transparent plastic foils serves for homogenization of the seed.

3. Data taking

Typically the data acquisition is done at different phases per period, typically 8 or 16 data points. Each set consists

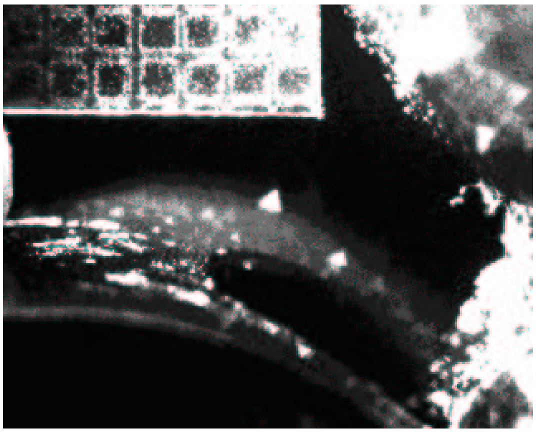

Figure 1: *View of the embouchure by the PIV camera. The blow hole and the labium is seen in the center, upper and lower lip at the upper right and lower right corner, respectively. The air jet leaves the flue at the right border between the lips. Only for calibration the grid with a pitch of 1 mm at the upper left corner is inserted.*

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 exposure of the acoustic wave the seeded air flow was operated for some time in order to fill the box with seeding. The frequency was set exactly to the sounding frequency of the flute being somewhat displaced from the resonance frequency due to the impedance change at the embouchure. It was checked that the phase as well as the relative amplitude of the velocity field remained fixed with respect to the reference pressure of the resonator while sweeping across the resonance.

Typical values for the operation of the flute are given in Table 1 for the nominal frequency f_{nom}, the blowing pressure p_{blow}, the jet speed U_{jet}, the acoustic velocity v_{acmax}, and the effective pressure amplitude of the resonator at the 'Gis' key A_{res}^{eff}.

Table 1: *Typical values of flute operation for investigated regime.*

f_{nom}	p_{blow}	U_{jet}	v_{acmax}	A_{res}^{eff}
Hz	Pa	m/s	m/s	Pa
570	126	15	1.3	45
570	474	26.3	2.5	213
1140	252	19.6	1.6	60
1140	553	29.5	3.5	232

4. Evaluation of the data

A typical velocity field is displayed in Fig. 2 for 1140 Hz and a moderate blowing pressure of 252 Pa. The jet is moving downwards into the flute, creating a vortex before reaching the labium. The vorticity is calculated in a 3 × 3 field in terms of interrogation areas. The vorticity is high at the upper and lower rim of the jet forming a continuous vortex street. As compared to free jet, where the vorticities would cancel, there is a net vorticity due to the positive curvature as the labium is approached, see Fig. 3.

The acoustical field at the same phase is displayed in Fig. 4. Since the acoustical field is ahead of the jet displacement, it is near its maximum value. The phase difference shrinks as the jet speed increases. The vorticity of the field is small at the mouth pressures and frequencies investigated, so that a potential flow can be assumed. The displacement amplitudes are <0.7mm for 570 Hz and <0.5mm at 1140 Hz, therefore small compared with distance flue-labium.

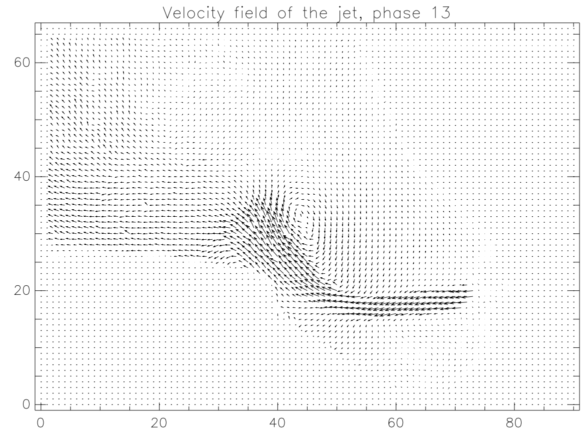

Figure 2: *Velocity field of the flute at 1140 Hz and a blowing pressure of 252 Pa, see also Tab. 1. The phase corresponds to the zero crossing of the pressure amplitude. The ordinate and abscissa are the y- and x- axis, one unit corresponds to ∼0.144 mm.*

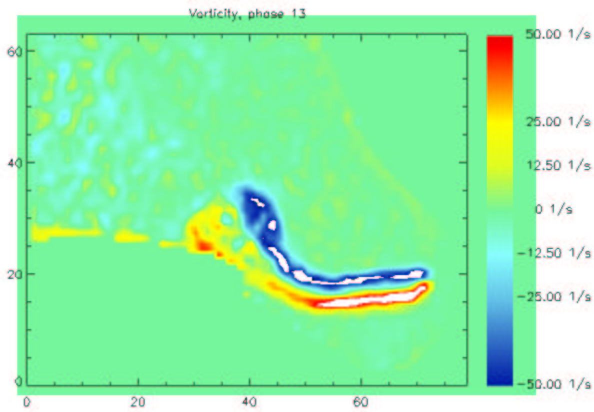

Figure 3: *Vorticity of the jet derived from the velocity field seen in Fig. 2. The upper rim has negative vorticities.*

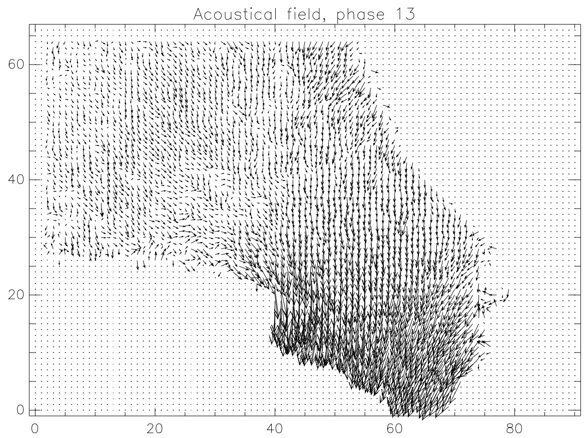

Figure 4: *Acoustical field at the embouchure generated the external source*

5. Evaluation of the vortex sound power

The final evaluation concerns the power density, the integration over the investigated volume. It is assumed that there is no dependence along the axis of the flute, therefore the volume has an extension of 9.5 mm according to the size of the flue. Finally the averaging over one period is done.

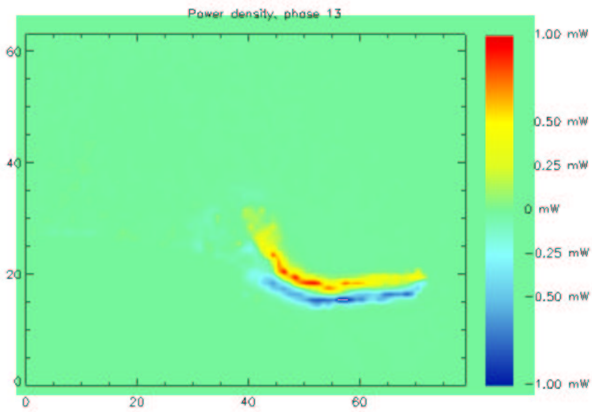

Figure 5: *The power density as given by the term of equation 2 in units of mW/cm^3. The upper rim has positive values.*

We take the convention that a positive net power of the system delivers acoustical energy.

$$P_{vort} = -\frac{\rho_{air}}{T} \int (\vec{\omega} \times \vec{U}_{jet}) \vec{v}_{ac} dV\, dt. \tag{1}$$

with the density of air ρ_{air}, the vorticity $\vec{\omega}$, the acoustical velocity $\vec{v}_{ac}$.

The integrand corresponding to the power density p_{vort} is interesting to investigate in detail

$$\frac{dp_{vort}}{dV} = -\rho_{air}(\vec{\omega} \times \vec{U}_{jet})\vec{v}_{ac}. \tag{2}$$

This expression is displayed in Fig. 5.

At the flue exit the integrated power density is near zero as expected from the vorticity of the jet, which are equal in absolute value, and from the small gradient of the velocity field. Downstream the power density of the upper and lower boundary of the jet is not balanced any more and yielding a positive net term from the upper part of the vorticity. Finally a vortex is shed as the jet sweeps across the labium.

It is obvious that the balance is delicate since the power of a vortex street by itself represents a value of an order of magnitude larger than the integrated result.

In this investigation the integration volume is taken over the total visible volume. It appears that there are no distortions in the calculated value due to the rim of the embouchure even if the jet dives into the flute.

Other phases are less efficient for the power production except of the one which is 180° apart, when the jet is reappearing with negative curvature from below. Since the acoustical field switched sign as well the result is again positive. A double peak structure with the phase angle is observed.

6. The vortex sound power and the comparison with the acoustical power

6.1. Acoustical power

The setup as used for the PIV measurements has been moved to the Fraunhofer Institut für Bauphysik, Stuttgart in order to measure in reverberation room the power at a given frequency and blowing pressure. The frequency spectrum was recorded in 1/3 octaves. At blowing pressures investigated it was seen that at frequencies of 570 Hz and 1140 Hz higher harmonics contribute not sizable to the integrated power. The power as a function of the pressure amplitude A_{res} was parameterized as

$$P_{ac} = C(f_{nom}) \cdot A_{res}^2. \tag{3}$$

where $C(570Hz) = (0.3 \pm 0.03)10^{-4}$ and $C(1140Hz) = (0.4 \pm 0.04)10^{-4}$ are the adjusted constants.

The maximum power is in accordance with values produced by a flutist playing '*forte*' [7].

6.2. The quantitative comparison

Both power values P_{vort} and P_{ac} are plotted in the Fig. 6 and Fig. 7. The sign of the power is positive. Moreover the dependence of P_{vort} on the acoustic sound level scales in a linear fashion. The line indicates the expected acoustical power. The vortex sound power is slightly overshooting the acoustical power.

7. Discussion of the results

First it should be stated that the separability of the jet properties during the operation and the acoustical field is assumed in order to extract the vortex sound term. Here,

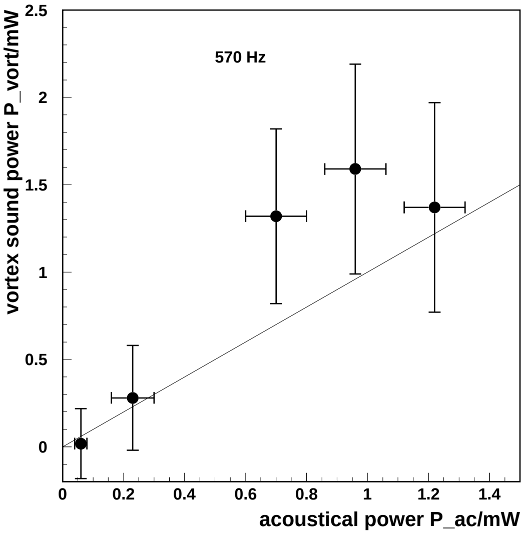

Figure 6: *Power of the vortex sound term plotted as a function of the acoustical power at 570 Hz*

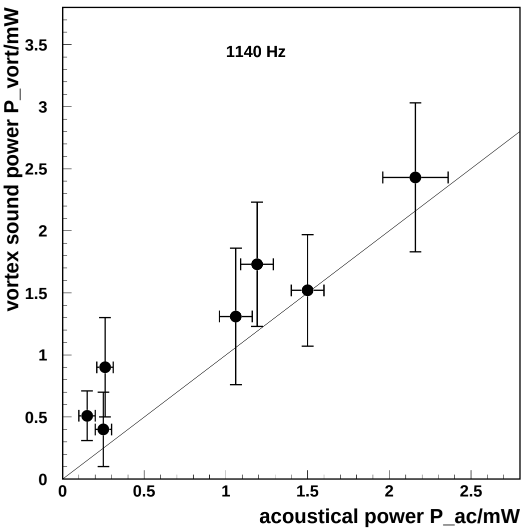

Figure 7: *Power of the vortex sound term plotted as a function of the acoustical power at 1140 Hz*

the acoustic speed is deliberately kept one order of magnitude below the jet speed. This approximation might fail at higher sound power levels.

Above findings have to be taken with care: Especially for the case of 570 Hz the view of the jet is partially obstructed by the embouchure. The size of the effect might be estimated by a symmetry argument as given above. The error bars includes an estimation of the effect. Some correction has been made for the 570 Hz case, as the visible jet is cut by the embouchure by an angle being different from 90° with respect to the jet velocity. Otherwise this would lead to an overestimation the power by 10%.

The uncertainty due do to changes in the geometry may be estimated from different series of measurements. It is difficult to quantify. However the results of the higher frequency seem more robust. It was taken care that the geometry was optimized at each frequency for maximum pressure amplitude. Some of the parameters are critical such as the distance of the flue exit to the labium and the tight cover of the lower lip across the blow hole. In the steady state operation the height of the labium seems to be rather insensitive as well as the exact rotation of the flute around its main axis.

The height of the flue has an dramatic effect, however.

In a more general context the author is aware of investigations of vortex sound by Kambe [8], recently by Elredge [9]. The first reference does not quote absolute values of the power, and the second one deals with acoustic absorption in ducts with absorption coefficients being reproduced in a quantitative way.

8. Conclusion

For normal sound levels the measurement of the vortex sound term is in good agreement with the acoustical power. This supports the hypothesis that the sound generation in flue instruments results from the vortex sound terms of the jet as a whole.

9. Acknowledgments

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10. References

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