Vortex sound in recorder-and flute-like instruments: Numerical simulation and analysis

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Abstract

The sound generation in small flute- and recorder-like geometries is studied by three-dimensional fluid-acoustic simulations using the lattice Boltzmann method (LBM). The vortex sound analogon of Howe allows us to evaluate the power of the vortex sound from the simulated flow field in the mouth of the instrument. In this context the determination of the acoustical particle velocity field is a crucial point. In this paper Helmholtz decomposition is employed to reconstruct the acoustical particle velocity from the total velocity field. The air jet exerts a net force on the sound field thus performing work. The analysis of the temporal and spatial distribution of vortex sound power shows that sound is mainly produced in a limited region within the jet. Depending on the geometry of the instrument heavy flow-acoustic losses can occur severely affecting the efficiency of the sound production process. Flow data obtained by numerical simulation and preliminary PIV measurements will be compared.

INTRODUCTION

Since pioneering works of Powell [Powell, 1964] and Howe [Howe, 1975] the concept of vortex sound gained more and more attention in present times. This physically intuitive concept how sound is generated by a vortical low Mach number isentropic flow successfully explained flow-acoustic problems like flow induced pulsations in duct systems [Kriesels, 1995] or self sustained oscillations by a flow around a plate in a duct [Tan, 2003]. In musical acoustics Bamberger [Bamberger, 2004, 2005] showed that the total radiated sound power of a flute scales with the mean vortex sound power generated by the air jet. This lets conclude that vortex sound is the only relevant source of sound to drive the flute. In this paper vortex sound in flute- and recorder-like instruments will be studied by numerical simulation.

FLOW-ACOUSTIC SIMULATIONS WITH LBM

The lattice Boltzmann method (LBM) is a relatively new numerical approach for simulating fluid dynamic and acoustic problems based on the space-time discretization of the Boltzmann equation. For applications in (musical) acoustics and low Mach number flow-acoustics, it is becoming a compelling alternative to the traditional continuum-based methods due to its computational simplicity and its ability to solve acoustic and fluid dynamic scales in a single calculation. Furthermore, numerical damping, a serious issue inherent to many continuum-based fluid dynamic algorithms, is nearly absent in LBM. Nevertheless, there remain a couple of tasks that still need to be addressed, among them the possibility of representing fluids with low kinematic

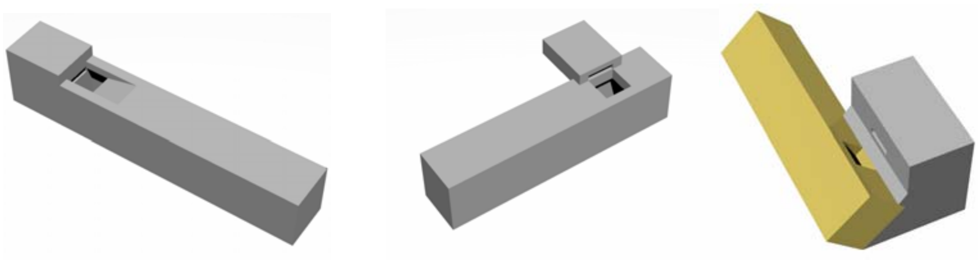


Figure 1: Geometries of the studied instruments: recorder, flute 1 and flute 2.

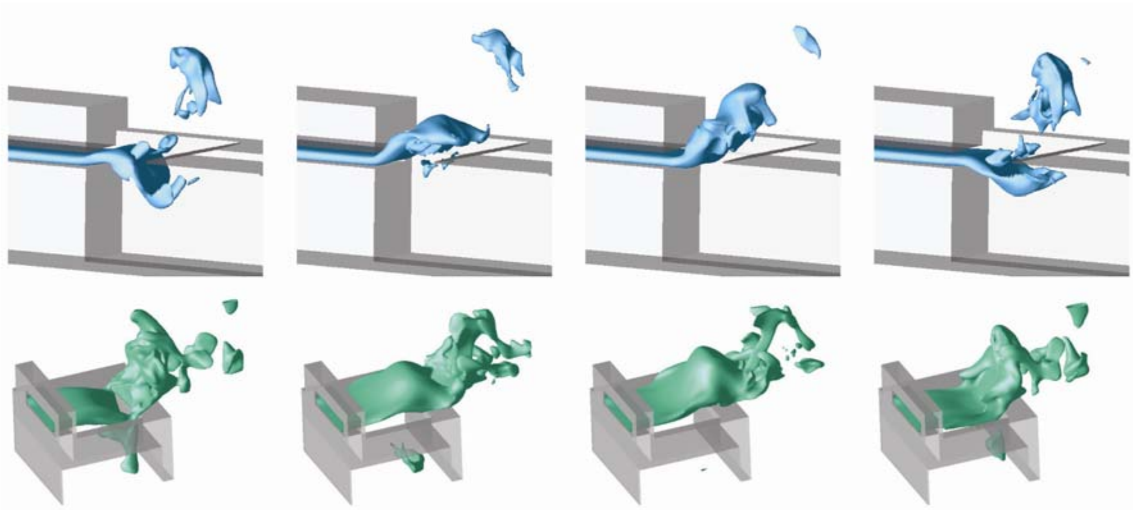


Figure 2: Snapshots of iso-velocity surfaces within one duty cycle in the recorder-like instrument (top) and in the mouth of flute 1 (bottom) using a three-dimensional LBM.

viscosities. Low viscosity LB simulations often result in high frequency noise, even in models with multiple relaxations times [d'Humières, 2002]. One solution for this problem is found by raising both, the kinematic and the bulk viscosity.

This has been the approach applied here to simulate the aero-acoustics of flute- and recorder-like systems with a three-dimensional multiple relaxation times LB model (figs. 1 and 2). Small stopped instruments of 6 cm total length and 1x1 cm resonator cross section were modeled, one recorder-like geometry and a square transverse flute, having in common the mouth area of 7x7 mm, a rather long flue of 15x7x1.5 mm and a distance of 7 mm from the flue exit to the labium edge. The flute was modeled in two different setups: Flute 1 has a flue with large vertical offset; its bottom coincides with the upper edge of the 90° labium. Additionally the jet attacks the labium under 0°. In flute 2, a more realistic setup, the jet attacks the labium symmetrically under 45°. These instruments operating at their fundamental frequency were simulated at different jet speeds. After steady state oscillation was reached flow data was sampled to be analyzed in a post-processing step that will be discussed below.

VORTEX SOUND IN FLUTES AND RECORDERS

Vortex sound theory

The vortex sound theory for low Mach number isentropic flow [Powell, 1964; Howe, 1975] describes the generation and absorption of sound by interaction of a vortical flow and a potential flow $\mathbf{u} = \nabla\varphi$, with φ being the scalar potential. The vortical flow component propagating with a velocity $\mathbf{v}$ and bearing a vorticity $\boldsymbol{\omega} = \nabla \times \mathbf{v}$ exerts a Coriolis force density

$$\mathbf{f} = -\rho(\boldsymbol{\omega} \times \mathbf{v}) \tag{1}$$

on the potential flow field thus performing work. In the case of the potential flow being the acoustical particle velocity field $\mathbf{u}_{ac}$ sound is generated if there is a surplus of the then so called vortex sound power

$$P_{ac}(t) = -\int \rho(\boldsymbol{\omega} \times \mathbf{v}) \cdot \mathbf{u}_{ac}\, dV \tag{2}$$

and sound is absorbed if P_{ac} is negative. Note that both, the Coriolis force and $\mathbf{u}_{ac}$ must be fluctuating quantities in order to obtain non-vanishing mean power.

Determination of the sound field

The above setup is rather academic; the vortical and the potential flow field are assumed to be known independently of each other. In the reality of an experiment or a CFD simulation both flow components are part of the total solution of the fluid dynamic equations. So the acoustic particle velocity $\mathbf{u}_{ac}$ needs to be reconstructed.

One approach uses simple models mostly based on plane wave concepts to get an estimate of $\mathbf{u}_{ac}$. In symmetric geometries this may lead to acceptable solutions; in instruments with an acute-angled labium like the recorder a plane wave solution in the mouth will be far from reality. A second approach uses a separate measurement of the acoustical problem only. Low amplitude measurements of acoustical problems fall into this category. Bamberger [Bamberger, 2004a, 2004b, 2005] measured the velocity field in the mouth of a flute externally excited by a loudspeaker to determine $\mathbf{u}_{ac}$. The above mentioned plane wave problem is circumvented here but convective effects occurring in blown flutes will be excluded.

Both approaches could be applied in the analysis of computer simulations as well. We follow a different path that involves only data already captured in the numerical simulation of the total problem.

Numerical decomposition of the velocity vector field

Howe [Howe, 1998, 2003] suggests splitting the total velocity field $\mathbf{V}$ into two components,

$$\mathbf{V} = \mathbf{v} + \nabla \varphi\,. \tag{3}$$

The solenoidal part $\mathbf{v}$, with $\nabla \cdot \mathbf{v} = 0$, includes the whole *incompressible* component of the velocity. The scalar potential φ describes *compressible* motions. This procedure is also known as *Helmholtz decomposition* of a vector field.

Howe then defines the temporal fluctuating part of the potential field to be the (fictitious) acoustical particle velocity $\mathbf{u}_{ac}$:

$$\mathbf{u}_{ac} = (\nabla \varphi)'\,. \tag{4}$$

The reminder of the total flow field will be referred to as the velocity field of the jet $\mathbf{v}_{jet}$:

$$\mathbf{v}_{jet} = \mathbf{v} + \overline{\nabla\varphi}, \tag{5}$$

including the solenoidal vector field $\mathbf{v}$ and the mean potential field $\overline{\nabla\varphi}$. The vortex sound power (VSP) in eq. (2) then reads

$$P_{ac} = -\int \rho\left(\boldsymbol{\omega} \times \mathbf{v}_{jet}\right) \cdot \mathbf{u}_{ac}\, dV\, . \tag{6}$$

We determine $\mathbf{u}_{ac}$ by numerically solving the Poisson equation for the scalar potential φ together with von Neumann boundary conditions

$$\nabla^2\varphi = \nabla \cdot \mathbf{V} \qquad \text{in the interior,} \tag{7}$$

$$\nabla\varphi \cdot \mathbf{n} = \mathbf{V} \cdot \mathbf{n} \qquad \text{at boundaries,} \tag{8}$$

with $\mathbf{n}$ being the normal vector of the boundary.

The equally spaced flow data facilitates the discretization of the Poisson equation with second order finite differences. We solve this sparse linear system of equations iteratively. In three dimensions we get a huge number of degrees of freedom. Even if we decompose only flow data of the mouth region we end up at about 1.5 millions of equations to solve.

During steady state oscillation the flow field in the instruments' mouth was sampled at 16 phase steps through the acoustic cycle. This data was used for the vector field decomposition. The beginning of an acoustic cycle is determined by the pressure maximum at the stopped end of the pipe. At that moment the acoustical particle velocity in the mouth of the instrument is zero and starts pointing outwards the instrument. Fig. 3 shows examples of the sound field in the central section of the mouth of a recorder-like and of a flute-like stopped pipe.

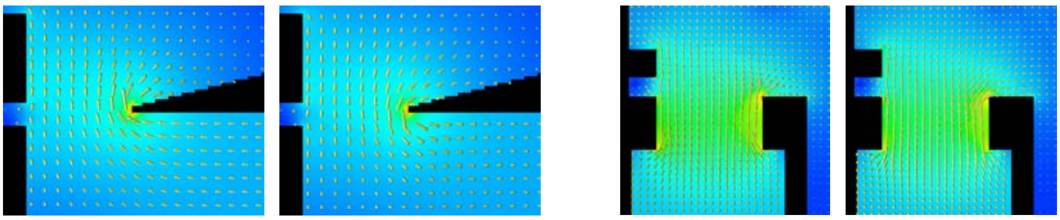


Figure 3: Acoustical particle velocity field at $t/T_0 = \pi/2$ and $3\pi/2$ in the mouth of the recorder (left) and of flute 1 (right). In both cases the v_{jet} = 42 m/s. In the recorder u_{ac} is 9 m/s at the center of the mouth and 36 m/s at the labium tip. In flute 1, due to the large offset of the flue, u_{ac} is only 4.6 m/s at the center of the mouth and 10 m/s at the labium tip.

The magnitude of the acoustical particle velocity of 25% of the jet speed in the recorder and of 10% in flute 1 which has a largely offset flue may seem rather large, but there are some factors to be considered concerning acoustical losses: First, LBM is an isothermal method, so only viscous but no thermal losses occur. Second, in such a short pipe of 6 cm length viscous losses are also small. And third, radiation happening only at the non-stopped end of the resonator is usually a minor loss factor at the fundamental frequency.

PRODUCTION AND LOSS OF VORTEX SOUND

Vortex sound power (VSP) in the recorder

In flue instruments the jet can be seen as a pair of shear layers parallel to the mouth opening. Sound generation and sound absorption always happens pairwise. In the first half-period sound is produced by the lower layer and absorbed by the upper; in the second half-period as the direction of u_{ac} changes from outwards to inwards the layers switch their role. Most of the generated sound is instantaneously absorbed; only 10% remain to drive the standing wave in the instrument. The bottom row in figure 4 shows the effective VSP density, which is the VSP density of the both layers summed up in vertical direction. It can be noticed that net sound production, red colored, takes place in a rather narrow zone emerging approximately midway the flue exit and the labium edge, and then is propagated downstream across the labium. The comparison with the instantaneous VSP density (top row in fig. 4) exhibits that net sound generation occurs where the jet has maximum curvature. The zone downstream the flue exit is mainly absorptive. The main losses occur in the second quarter of the period; the downstream region of the jet is now deflected maximally outwards in an acute angle to the sound field, thus unable to gain VSP.

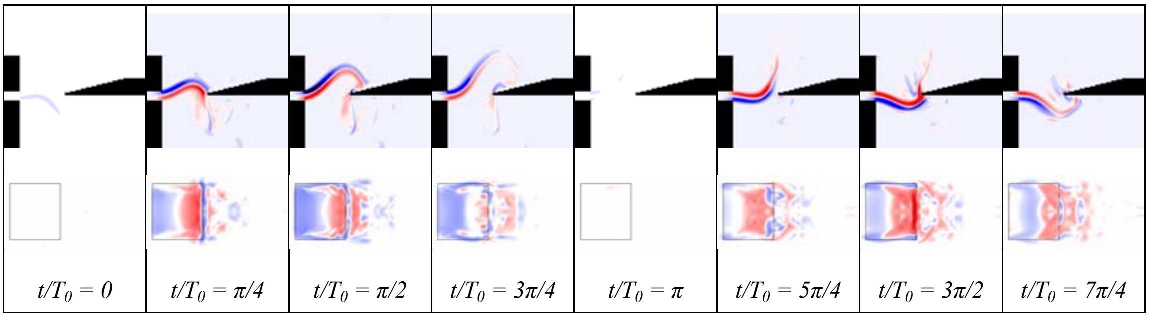


Figure 4: Instantaneous VSP density in the central cross section within one duty cycle (top) and effective VSP density (bottom) at v_{jet} = 46 m/s; red: sound production, blue: sound absorption. The contours of the mouth are indicated by a square, left edge: flue, right edge: labium.

Total net VSP and mean VSP of this “push-pull” double action is given in fig. 5. With increasing jet velocity the gain in sound power as well as the loss especially in the second quarter of the period increases.

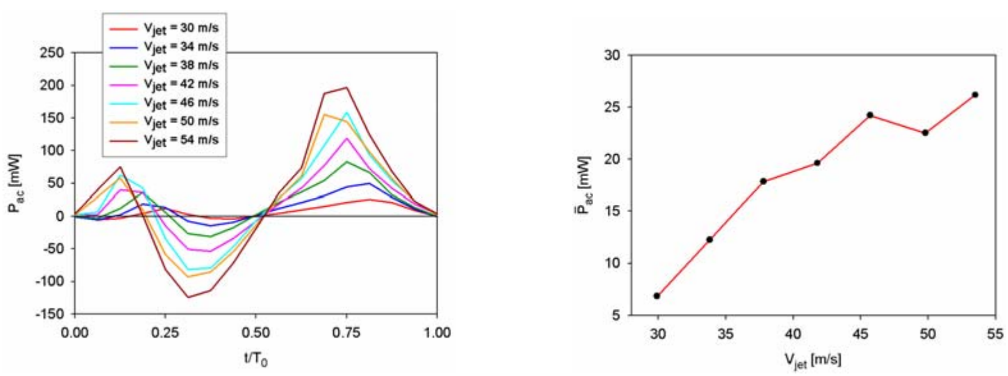


Figure 5: Total net VSP within one duty cycle (left) and mean VSP at different jet speeds (right)

Vortex sound power (VSP) in flute 1

The sound generation in flute 1 resembles the recorder in many points. Nevertheless there are some noticeable differences: The maximum sound production always happens upstream the labium (see the second and seventh column of fig. 6). Processes at the lateral boundaries of the jet now become import; in the first half-period they act strongly absorbing, in the second half-period sound generation in the lateral boundary zones considerably contributes to the net surplus of VSP.

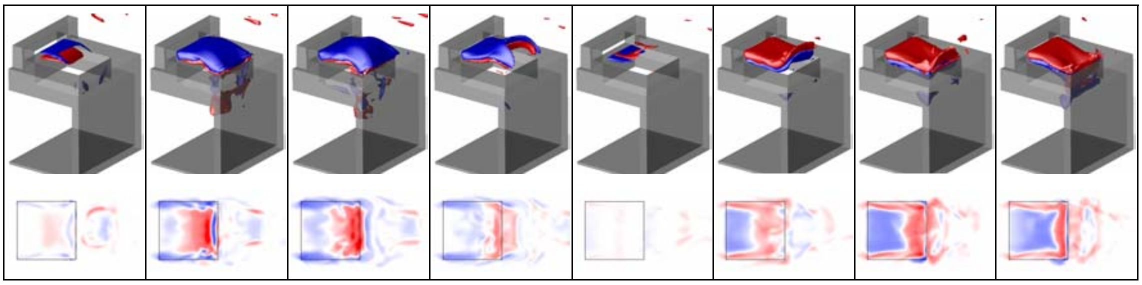


Figure 6: Iso-surfaces of the VSP density in flute 1 (top) and effective VSP density (bottom) at v_{jet} = 42 m/s 1 within one duty cycle; red: sound production, blue: sound absorption. The contour of the mouth is indicated by a square, left edge: flue, right edge: labium

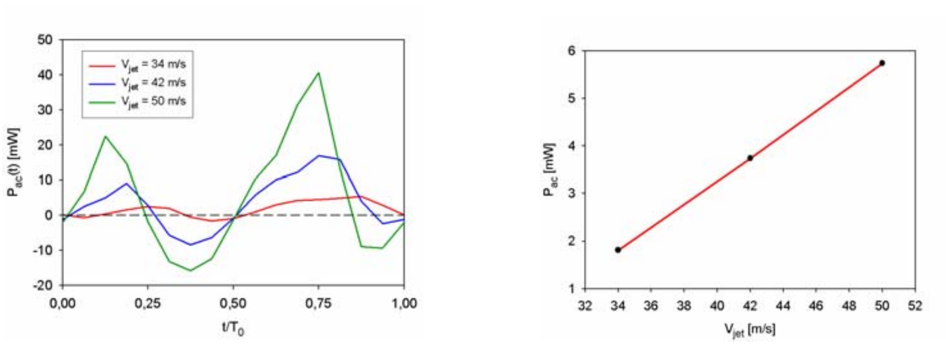
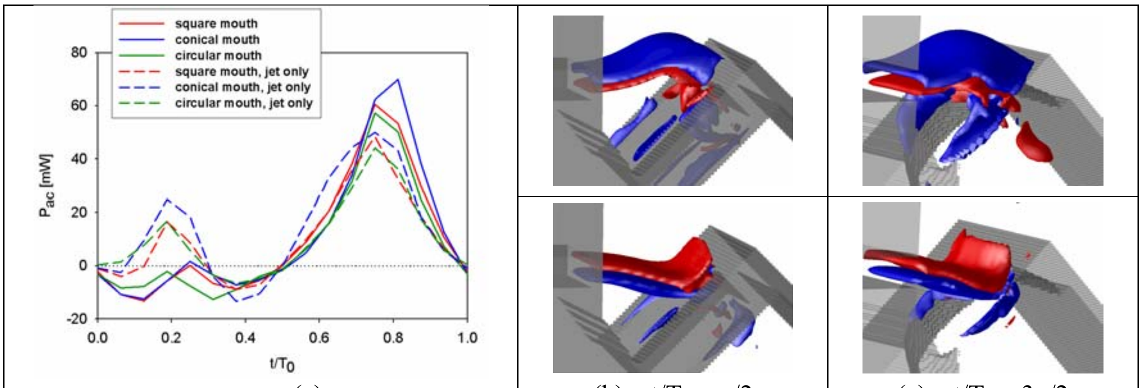


Figure 7: Total VSP within one duty cycle (left) and mean VSP at different jet speeds (right) in flute 1

Vortex sound power (VSP) in flute 2

Towards to a more realistic setup, the pipe of flute 2 is rotated 45° and the jet attacks the labium edge symmetrically. Three different riser geometries, a cuboid, a circular and a conical undercut were studied.

In all three riser setups heavy losses occur, especially during the first half-period completely overriding any sound generation (solid lines in fig. 8a). An examination of the spatial distribution of the VSP density (figs. 8b and 8c) reveals their origin: At the sharp lateral edges of the riser, fairly distant to the jet flow, the acoustical particle velocity triggers vortex shedding whenever it becomes large which is the case at $t/T_0 = \pi/2$ and $3\pi/2$ in the middle of every half-period. This attenuates the sound field. This relationship is furthermore confirmed by the evaluation of the VSP that lies within the jet (dashed lines in fig. 8a). Here the double peak nature of the sound generating process as known from the previous examples is restored.



(a) (b) $t/T_0 = \pi/2$ (c) $t/T_0 = 3\pi/2$

Figure 8: Total VSP (solid lines) and VSP within the jet (dashed lines) within one duty cycle in flute 2 with three different riser geometries (a). Iso-surfaces of the VSP density in the cuboid riser (b) and in the conical riser (c) at the moments of maximum u_{ac}. Acoustically induced vortex sound losses occur at the lateral edges of the riser

PIV-MEASUREMENTS

Preliminary PIV measurements of a recorder-like instrument could be made using Andreas Bamberger's endoscopic PIV setup at the University of Freiburg. The head of a commercially available soprano recorder was extended by a stopped tube. Unfortunately the simulation of the exact recorder geometry was not successful; therefore we compare the measurement qualitatively with a simulation of the stopped recorder-like instrument previously discussed. The simulation was chosen to be best comparable in Strouhal and Reynolds number: $Str^{PIV} = 0.13$, $Str^{LB} = 0.17$ and $Re^{PIV} = 840$, $Re^{LB} = 540$. Despite the differences in geometry and jet velocity there are quite a number of similarities. Fig 9 gives a first rewarding glance at the flow-acoustics in a recorder.

CONCLUSION

We have shown that analysis of the vortex sound power density in flutes and recorders can reveal many details of the sound generation process. Sound generation happens rather local; absorption seems to be more spatially distributed. In the recorder, due to its acute-angled labium, the acoustical particle velocity has a much larger gradient towards the labium than in the obtuse-angled flute riser. Consequently the sound generation in the recorder concentrates more at the labium, whereas in the flute it is located upstream the labium. Furthermore the VSP analysis shows how sharp-edged risers can lead to heavy losses due to acoustically induced vortex shedding.

Many thanks to Prof. Andreas Bamberger for his kind support in providing access to his PIV apparatus and for all the fruitful discussions.

REFERENCES

Bamberger, A. (**2004a**), "Vortex sound of flutes observed with Particle Image Velocimetry". *Proceedings of the 18th ICA*, Kyoto, 2004

Bamberger, A. (**2004b**), "Operation of Flutes at Low Pitch Investigated with PIV", *Proceedings of ISMA*, Nara 2004

(a)

(b)

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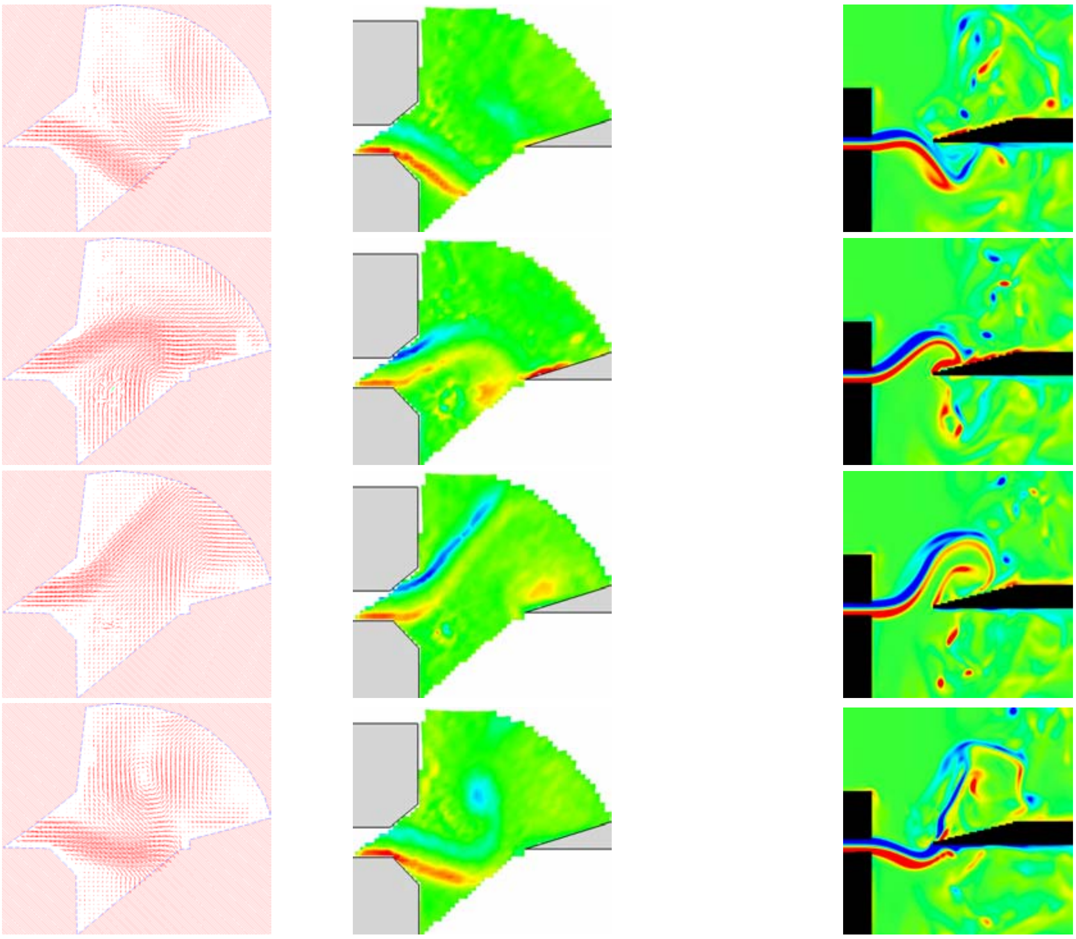

Figure 9: PIV velocity vector map of the mouth region of a soprano recorder (first column), vorticity calculated from the measurement (second column) and vorticity of the simulation (third column) at t/T_0 = 0, π/2, π and 3π/2

Bamberger, A. (**2005**), "Vortex sound in flutes using flow determination with Endo-PIV", *Proceedings of Forum Acusticum Budapest* 2005, pp. 23-30

d'Humières, D.; Ginzburg, I.; Krafczyk, M.; Lallemand, P.; Luo, L.-S. (2002), "Multiple-relaxation-time lattice Boltzmann models in three-dimensions", *Philosophical Transactions of Royal Society of London A* 360(1792), pp. 437-451

Howe, M.S. (**1975**), "Contributions to the theory of aerodynamic sound with applications to excess jet noise and the theory of the flute", *J. Fluid Mech.* 71, pp. 625-673

Howe, M.S. (**1998**), *Acoustics of Fluid-Structure Interactions*, Cambridge University Press, 1998

Howe, M.S. (**2003**), *Theory of Vortex Sound*, Cambridge University Press, 2003

Kriesels, P.C.; Peters, M.C.A.M.; Hirschberg, A.; Wijnands, A.P.J.; Iafrati, A.; Riccardi, G.; Piva, R.; Bruggeman, J.C. (**1995**), "High amplitude vortex-induced pulsations in a gas transport system", *Journal of Sound and Vibration* 184 (2), pp. 343-368

Powell, A. (**1964**), "Theory of Vortex Sound", *J. Acoust. Soc. Am.* 36(1), pp. 177-195

Tan, B.T., Thompson, M.C., Hourigan, K. (**2003**), "Sources of acoustic resonance generated by flow around a long rectangular plate in a duct", *Journal of Fluids and Structures* 18 (6), pp. 729-740