Flow-Acoustic Interaction in Acoustic Resonators

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Abstract

In flue-like instruments, the tonal sound is generated due to non-linear flow-acoustic interactions. The production and absorption of sound occurs when the energy of the vortical flow converts to the acoustical energy and vice versa. This work reports the ongoing research and on the flow-acoustic feedback phenomenon, and the methods available. Furthermore, a two-dimensional test case for studying the sound generation in a flue-like instrument is presented, and first results of the oscillating behavior of the instrument are shown. For this purpose, compressible Navier-Stokes equations are solved in the time domain and linear acoustics are considered in the frequency domain. Finally, general effects of flow-sound interactions are discussed.

Introduction

The mouthpiece of a flue-like instrument consists of a slit, a sharp edge (a wedge) and a resonator in between. As the air is blown into the mouthpiece, it separates from the slit and forms a jet. This jet travels along the neck of the resonator towards the wedge, oscillating at the neck of the resonator. These oscillations are coupled with the resonator. Here two systems are identified: a hydrodynamic system; a vortical flow field associated with the vortex shedding; and an acoustical system; a potential flow field, with fluctuations associated with the acoustic resonance. The energy exchange between the two systems, i.e. the vortical flow and the acoustic resonance is responsible for generation and propagation of sound waves, and maintaining the self-sustained oscillations [1, 2].
From a numerical perspective, the prediction of sound generated by the flow is challenging, mainly due to different scales of flow and acoustic fields. A numerical calculation requires to solve unsteady flow and the sound waves simultaneously. On the other hand, energy levels of the flow are typically several orders of magnitude larger than the energy of the sound waves, while the wavelengths are typically several orders of magnitude larger than length scales in the flow [3].

The solution of the unsteady compressible Navier-Stokes equations in time-domain is able to capture the non-linear and viscous effects for aeroacoustic calculations. In general, aero-acoustic methods are divided into two categories: direct and hybrid methods [4].
In direct methods, the unsteady flow and the generated sound are calculated simultaneously. In these methods, the domain must contain the flow-region where the sound is generated, and the near-field. The grid resolution must be fine enough to resolve both flow and sound fields adequately. Furthermore, For compressible Navier-Stokes equations, the time step size, defined by the CFL number, needs to be extremely small. Therefore, the computation cost of these methods is high. Direct methods are best used when receivers are located in near field.
For low Mach number flows, the receivers in the near field are primarily influenced by local hydrodynamic pressure fluctuations and the flow can be assumed to be incompressible. Here, the time step size is not restricted by the CFL number [3]. However, incompressible calculations cannot provide information about resonances and the flow-acoustic feedback phenomenon [5].

Due to the high computation cost of direct methods, the far-field sound is often calculated using hybrid approaches. The sound source region is treated using time-accurate solution of fluid dynamics, and often an acoustic analogy is used to calculate the sound in the far-field.
In hybrid approaches, it is assumed that the acoustic field has no influence on the flow. However, in some cases, such as self-sustained oscillations of a resonator, there is an acoustic feedback which alters the sound source significantly. Maintaining self-sustained oscillations is in general due to a feedback loop (Figure 1). For these applications, the theory of vortex sound formulations by Howe [6], Powell [7], and Doak [8] is most convenient to use [9].

Howe's theory was used by Richter and Fuß [10] to calculate sound production and propagation in case of a recorder. Based on RANS calculations, the authors identified two mechanisms for sound generation: vortex sound between the jet and the labium and pressure fluctuations acting on the labium. Using these mechanisms as dipole sound sources, they solved the Helmhotz equation to calculate the sound field. The sound generation mechanism is further studied by Richter and Stiller [11] using a high-order discontinous Galerkin scheme.

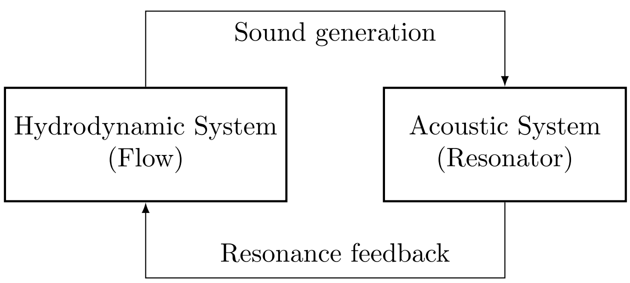
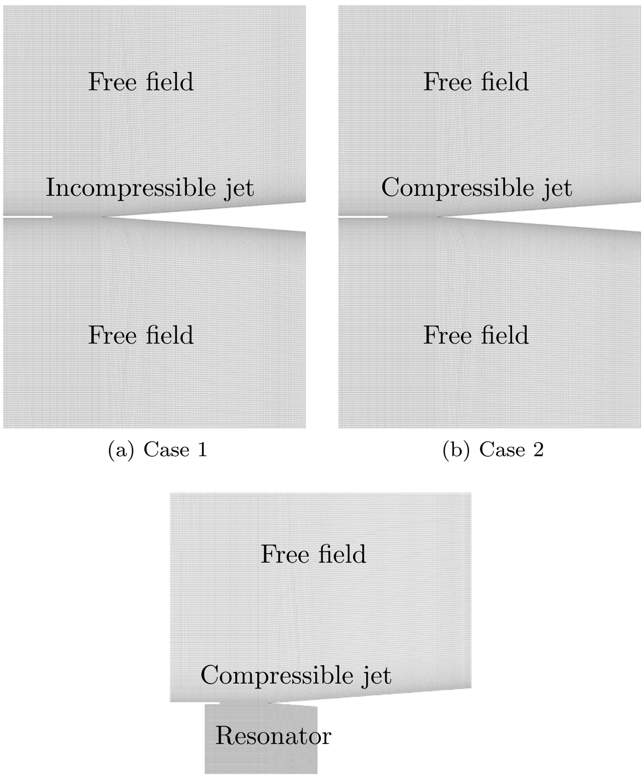


Figure 1: Flow-resonator feedback loop

In a recent publication, Fabre et al. [1] have discussed the applicability of the global approaches on aeroacoustic resonators. In their method, they couple a locally incompressible flow with an acoustical resonator with applying appropriate impedances as boundary conditions. Their method provides an insight into the feedback mechanism in simple systems such as whistling.

Method

A two-dimensional model consisting of a jet and a wedge was considered. This configuration leads to a self-sustained oscillation, which is correlated to a fundamental frequency. In this work, the focus is on these effects and additional turbulent noise is avoided. Three cases, as shown in Figure 2 were simulated. In the first two cases, the effect of compressibility on self-sustained oscillations of a jet was studied. In the third case, a resonator was coupled to the compressible flow configuration to study the change in flow-structure due to the flow interaction with the acoustic resonator. A direct comparison between cases 2 and 3 shows how the resonator affects the jet oscillations close to the edge and how the jet-wedge interaction is changed.



(a) Case 1 (b) Case 2

(c) Case 3

Figure 2: Simulation models; (a) jet-wedge, incompressible flow; (b) jet-wedge; compressible flow; (c) jet-wedge-resonator; compressible flow.

The geometry of the resonator in Figure 3, which is based on the real geometry of a clarinet mouthpiece, was reduced in size to minimize the Reynolds number in order to avoid turbulence disturbance. The structured grid consists of 46600 quadrilateral control volumes. ANSYS Fluent was utilized to solve the governing equations. This commercial package offers a second order Finite Volume Method (FVM) for spatial discretization and a second order Runge-Kutta method in time-domain. With a maximum CFL number of 0.1, the final time step size was 5×10^{-6} s.

At the upper and lower boundaries of the free field for the compressible flow, an acoustic non-reflecting boundary was applied to prevent reflections of acoustic waves into the domain. For stability reasons, a very slow flow inlet was introduced at the left boundary, and a zero pressure boundary condition was applied to the right boundary of the free field. Jet, wedge and resonator boundaries were non-slip walls.

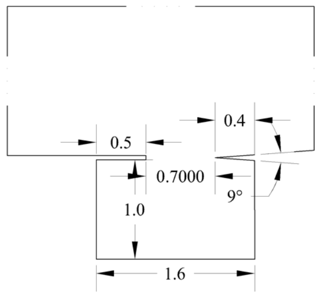


Figure 3: Geometry of the resonator; dimensions in cm.

Results and Discussion

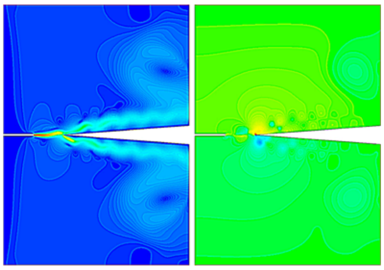
Compressibility Effect

Contours of pressure and velocity for incompressible and compressible simulations are shown in Figure 4 (a) and (b). A jet oscillates, hits the sharp edge, periodic vortices are formed and travel downstream and slowly disappear. For the incompressible flow the vortex shedding is mainly attached to the wedge, and two large vortices are formed downstream. Compressible calculations, however, show a different flow structure. As the flow hits the wedge, it separates from the surfaces, and two big vortices appear a both sides. The intensity of these two vortices changes alternatively as the jet oscillates.

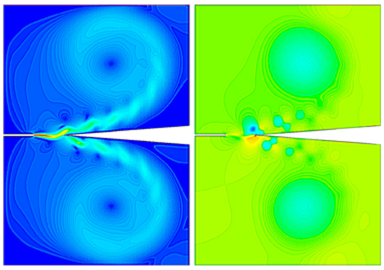
Resonator Effect

Figure 4 (c) shows a big vortex that is formed inside the resonator which affects the flow above the cavity, changing the jet oscillations drastically. In Figure 5, jet oscillation near the wedge during one period is shown.

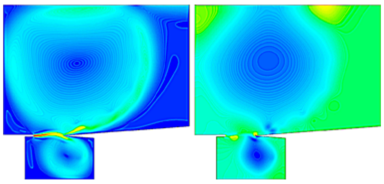
During the first half-cycle, the pressure inside the resonator decreases until it reaches the minimum at t=0.5T. At this point, the jet hits the wedge and separates from the wall, and the jet has the maximum downward displacement. The pressure inside the resonator starts to rise during the second half-cycle, and at the end of the cycle, the jet has its maximum upward movement. Furthermore, periodic vortices are formed downstream the resonator neck. Tracing a vortex that is produced downstream, shows that this vortex moves towards the sharp edge, and grows in size during this movement. As the



(a) Case 1



(b) Case 2



(c) Case 3

Figure 4: Periodic flow; Incompressible versus compressible flow; max velocity = 2 m/s; left: velocity contours; right: pressure contours.

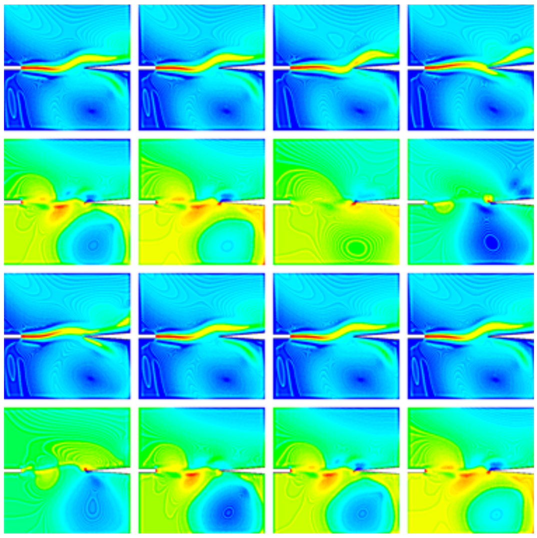


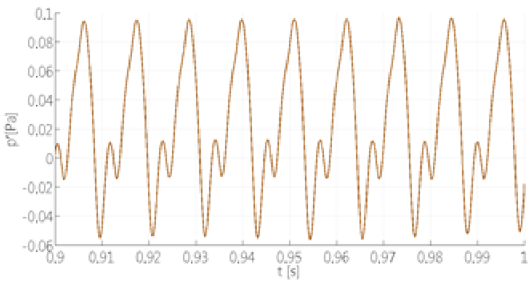
Figure 5: Jet-wedge-resonator oscillations in one period; upper row: velocity; lower row: static pressure; left to right top to bottom: t=0; t=0.05T; t=0.25T; t=0.5T; t=0.75T; t=0.95T; t=1.0T; t=1.05T.

vortex reaches the wedge, it is "stretched" and moves with a higher velocity. This is an indication of the effect of Coriolis acceleration in the fluid. Despite the different flow structure due to geometry configurations, this phenomenon is similar to what Nelson et al. have reported in their experimental and numerical studies of a resonator [12, 13].

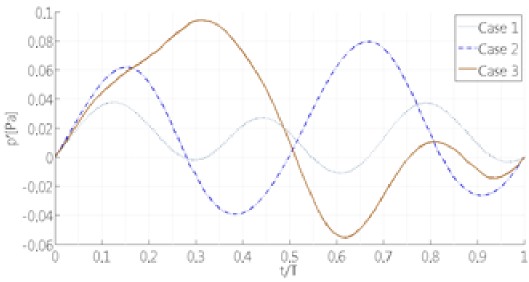
Here, a shear layer oscillation regime, as described by several authors, including [5] can be identified, which is known by the roll-up vorticity in the shear layer. The generated vortices travel with the mean flow inside the resonator, until they hit the walls of the resonator. At this moment, acoustic pressure waves are generated which propagate in the opposite direction. These waves interact with the shear layer at the upstream of the resonator lip. A big stationary vortex is occupying part of the resonator, which means the interaction between the shear layer and the flow inside the resonator is weak [5]. Swirling motion of the steady vortex is responsible for the low pressure region inside the resonator.

Frequency of Oscillation

In order to identify the frequencies of oscillation, time signals of fluctuating pressure have been recorded at a point in the shear layer in the middle of the jet and the wedge x=0.35cm and y=0 (0.35,0), where x and y indicate the distance from the center of the starting jet. Figure 6 (a) shows these fluctuations after the flow has been statistically converged. In Figure 6 (b), pressure fluctuations for all three cases at (p) in one period are shown. For all cases, two sinusoidal waves are observed in one period, which may be due to the effect of the vortex shedding on the wedge on jet oscillations. The jet oscillation period for the resonator case was T=0.011 seconds, whereas the period for other two cases was almost double (T=0.020 seconds).



(a)



(b)

Figure 6: Pressure fluctuations after reaching a periodic solution; (a) jet-wedge-resonator; (b) all cases in one period.

The power spectral density graph in Figure 7 shows that in the compressibility effects on the sound levels are negligible. It is worth noting that the results presented here need a comprehensive validation. Using the Ffowcs-Williams and Hawking's analogy, at a receiver located between the jet and wedge at (0.35,0), no difference between the incompressible and compressible calculations could be detected; the resonance frequency is about 60 Hz and the sound pressure level in both cases is about 39 dB. However, attaching a resonator to this configuration changes the jet-wedge behavior crucially. The resonances occur at frequencies about 20 and 90 Hz with a maximum sound pressure level of 71 dB. Although these results show a trend, which is the different frequency and amplitude for a resonator, this analogy is not valid for near-field calculations. Further studies will solve the sound field using direct methods.

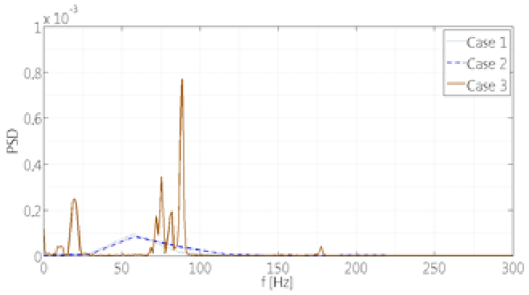


Figure 7: Power spectral density

Conclusion

Self-sustained oscillations in a jet-wedge-resonator configuration, similar to the mouthpiece of a flue-instrument, was simulated. At first, compressibility effects were studied on self-sustained oscillations of a jet-wedge setting. Results show that viscous effects due to compressibility change the flow structure, however, the first results show no influence of compressibility on frequency of oscillations, although the sound pressure level is higher for the compressible flow. Coupling an edge tone with an acoustic resonator will change the jet behavior drastically. The resonance occurs at a higher frequency of 90 Hz, and the sound pressure level is about 30% higher than a simple jet-wedge set up in free stream. Also, the sound power level is 71 dB, in contrast to 39 dB for the cases without a resonator. Although first quantitative results presented here need to be validated, they show a promising path for future work. In the next step, the study will go deeper into the phenomenon of energy exchange between the flow and acoustic fields. The final aim is to develop a calculation algorithm, in which incompressible Navier-Stokes equations are coupled with a Helmholtz solver for linear acoustic of the resonator, which produce results similar to that based on compressible Navier-Stokes equations.

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