DIRECT NUMERICAL SIMULATION OF THE FLOW IN A FLUE PIPE

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Abstract The flow behavior of a geometrically simplified flue pipe has been investigated by direct numerical simulation for jet Reynolds numbers of $Re = 368;\ 490;\ 613$. The flow process starts with the formation of a ring vortex at the flue exit, which travels towards the upper lip of the pipe. In the following Kelvin-Helmholtz instability appears at both sides of the jet, vortices are formed and an oscillating lateral movement of the jet set in. The vortices interacts with the upper lip, which leads to the generation of further opposite rotating vortices. After resonance is established in the pipe, the frequency spectrum of the quasi periodic state shows the expected fundamental frequency as well as several harmonics.

INTRODUCTION

Pipe organs can generate a high variety of different sounds in the full human acoustic range and beyond. In general two types of pipes are in use for sound generation, reed and flue pipes. The latter ones are investigated in this contribution. In flue pipes an oscillating plain jet of air stimulates standing sound waves in the body of the pipe. Over centuries the geometry of pipes have been developed by empiricism to receive registers of different timbre and an equal timbre within one register. In the last decades several theoretical, experimental, and numerical works have been carried out to understand the governing physical mechanisms [1, 2, 3, 4]. In this contribution a two dimensional direct numerical simulation is applied on a simplified pipe model to characterize the behavior of flow and frequency spectrum from the initial phase to a quasi periodic state.

MATERIAL AND METHODS

The simplified flue pipe is sketched in Figure 1. The fundamental dimensions are geared to that of a diapason, the main register of a pipe organ. At a pressure of $p_0 = 1013.25$ hPa, a temperature of 288.15 K, and air as fluid, the chosen length of the body L corresponds to a pitch of c^2 with a fundamental frequency of about 523 Hz. All walls are of zero thickness. At the flue exit a jet enters the domain with an uniform velocity profile of $u_0 = 9;\ 12;\ 15$ m/s. In points A and B data of the flow field are taken and analyzed.

Air has been considered as ideal gas. The compressible, two dimensional Navier-Stokes equations have been solved by the finite volume code OpenFOAM. The discretization in time and space is of second order. The dimensions of the computational space are $(14L \times 8.4L)$. The number of cells ranges from $2.4 \cdot 10^5$ to $1.4 \cdot 10^6$. A grid study has been carried out. For initial conditions the above mentioned pressure and temperature have been chosen as well as a velocity of zero. At the flue exit (width h) an inflow boundary condition has been set, at the outer boundaries a wave transmissive condition.

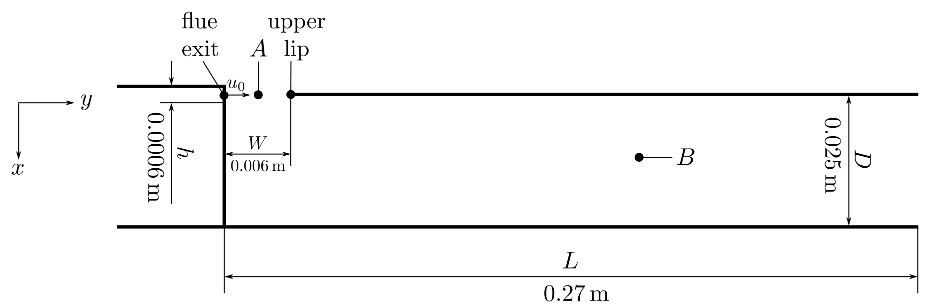

Figure 1. Simplified flue pipe.

RESULTS AND DISCUSSION

On the left side, Figure 2 represents the pressure fluctuations $p' = p - p_0$ at point A as function of time t for $u_0 = 15$ m/s. When inflow of air starts at the flue exit, a pressure wave with a circular front forms. At $t = 10^{-5}$ s the front reaches point A, which leads to maximum value of p'. The following smaller groups of peaks up to $t = 5 \cdot 10^{-4}$ s result from reflections of the wave at the inner pipe wall. In addition to the pressure wave a vortex ring develops at the flue exit and travels in direction of the upper lip (Figure 3). At about $t = 7 \cdot 10^{-4}$ s the right core of the vortex touches point A and the pressure

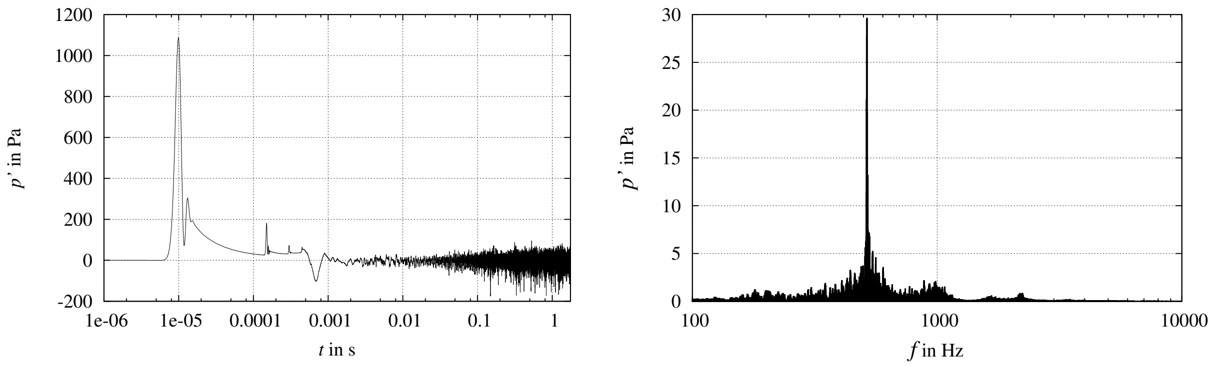

Figure 2. Left: Pressure fluctuations p' at point A plotted versus time t. Right: Frequency spectrum of pressure fluctuations at point B for quasi periodic state, both for $u_0 = 15$ m/s.

p' features a local minimum. The cruising velocity of the vortex increases with time and reaches a maximum at about $t = 8.4 \cdot 10^{-4}$ s. It has a slight component in negative x-direction, which results from the asymmetric geometric boundary at the flue exit and may be reinforced by the flow resistance in the pipe. While the vortex ring reaches the outer face of the upper lip at $t = 1.1 \cdot 10^{-3}$ s, a counter rotating vortex has formed at the inner face. The shear layer of the jet gets unstable at both sides (Kelvin-Helmholtz instability), vortices are generated and lateral oscillations of the jet set in. When reaching the upper lip, the vortices partially induce the formation of further counter rotating vortices inside and outside of the pipe. In the meantime the initial vortex circulates outside of the pipe and hits the oscillating jet at $t = 4.1 \cdot 10^{-3}$ s. Up to $t \approx 3 \cdot 10^{-1}$ s, standing waves build up in the body. In this time period the appearance of a dominating edge frequency was expected to appear. This was not the case and may be explained by the missing thickness of the upper lip.
On the right side, Figure 2 depicts the frequency spectrum of pressure for $t > 0.3$ s and $u_0 = 15$ m/s, taken at point B. The peak value at 519 Hz corresponds to the expected fundamental frequency. Further peaks at about 1000, 1650 and 2200 Hz represent the first to third harmonics. Towards higher harmonics the frequencies are shifted to higher values in comparison to the multiple of the fundamental mode, a phenomenon, which results from the frequency dependent reflection point of the standing waves [5]. The flow field of the quasi periodic state near the bottom of the pipe is characterized by a clockwise rotation, driven by the jet (Figure 3 at $t = 1.5$ s). Vortices, generated in the shear layer of the jet or at the upper lip, move around a center and interact with the jet. Vortex merging as well as vortex stretching can be observed. In accordance with literature [5], the fundamental frequency decreases disproportionately with decreasing jet velocity u_0.

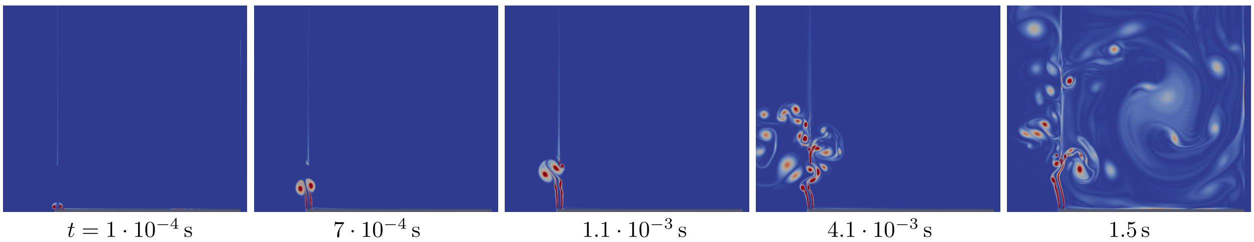

Figure 3. Field of vorticity near the bottom of the pipe at different times t.

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