Dynamics of fluidic oscillator jet: LES study

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Abstract. We study a turbulent jet generated by a fluidic oscillator using Large-eddy simulations in a range of Reynolds numbers $Re_d = 3000–30000$. The device represents $\Phi$-shaped configuration providing a strongly unsteady flow due to periodic oscillations based on the Coanda effect. Several simulation results are presented for a mesh convergence study, the analysis of the time-averaged statistics as well as the oscillation frequency against $Re_d$.

1. Introduction
A fluidic oscillator generates a spatially oscillating jet [1] which can be employed in many practical applications such as the control of separated flows [2] or mixing efficiency enhancement [3]. Although there are some extensive numerical studies in the literature [4, 5, 6], they typically employ URANS-based approaches. However, a set of eddy-resolving simulations of the fluidic oscillator [7] is still lacking which is the main objective of the present paper.

2. Computational details
We consider the non-dimensional filtered incompressible Navier–Stokes equations describing the fluid motion:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \frac{\partial u_i}{\partial x_j} = 0,$$

where $u_i$, $p$ are the components of the velocity field and pressure, respectively, $\tau$ represents the subgrid-scale stresses appearing in the Large-eddy simulation framework, in this study the subgrid-scale tensor is expressed using the dynamic Smagorinsky model [8, 9, 10]. Large-eddy simulations (LES) are performed using Nek5000 code [11] with a spatial discretization based on the spectral-element method (SEM) using Lagrange polynomials. Within SEM approach the computational domain is divided into hexahedral elements, where the velocity and pressure fields are approximated by high-order Lagrange polynomials of the order $N$ for both velocity and pressure fields. These polynomials are based on the Gauss–Lobatto–Legendre rule. For the time discretization an implicit third-order backward differentiation formula is used. The code has been extensively validated by many authors including our group [12].

We consider a spatially oscillating jet generated by the fluidic oscillator with the geometry considered in recent experiments [7] for Reynolds numbers $Re_d = U_0 d/\nu = 3000–30000$, based on the bulk velocity of the incoming flow $U_0$ and the nozzle width of the fluidic oscillator $d = 25$ mm. The computational domain shown in Fig. 1 from two viewpoints, where $x$, $y$ and $z$ are coordinates along...
Table 1: Details of the computational meshes: Nse is the number of spectral elements, Nnodes = Nse × N³ is the number of computational nodes, the time step is non-dimensionalized with U₀ and d.

| Polynomial order | Nₚₑ | Nnodes | time step |
|------------------|------|--------|-----------|
| 4                | 97870| 6263680| 2 × 10⁻³  |
| 6                | 97870| 21139920| 1.4 × 10⁻³ |
| 8                | 97870| 50109440| 0.9 × 10⁻³ |

the streamwise, transverse and spanwise directions. The streamwise length of the fluidic oscillator is Lₓ = 23.6d starting from a converging channel beginning with Lᵧ = 7.4d down to Lz = 1d height. The main chamber of the device is 7.6d in length ending up with a Lᵧ = 1d slot (−0.5 ≤ z/d ≤ 0.5). Inside the device the domain is Lz = 1d along the spanwise direction, while the unconfined area represents a Lₓ × Lᵧ × Lz = 21d × 28d × 10d rectangle. The unstructured computational mesh contains around 98 × 10³ spectral elements with the polynomial orders N = 4, 6 and 8 leading to 6.3 × 10⁶, 21.1 × 10⁶ and 50 × 10⁶ nodes, respectively (see Table 1). On the walls we set a no-slip boundary condition. The inflow is set by a uniform streamwise velocity in agreement with experiments [7], while the outflow corresponds to the Neumann condition.

Figure 1. The computational domain and coordinate system. The geometry is the same as in [7].

3. Results
Figure 2 shows the instantaneous field of the streamwise velocity in the middle cross-section x − y and z/d = 0 (symmetry plane of the computational domain) for all three values of N and Reₐ = 3000 for almost the same phase of the oscillation. The coarsest mesh captures all the essential large-scale dynamics allowing to rely on N = 4 further while N = 6 and 8 requires more computational time for a well-converged statistics which is still on the way.

Figure 2. The streamwise velocity field for N = 4, 6 and 8 and Reₐ = 3000 in x − y plane at z/d = 0.
Figure 3 demonstrates the internal dynamics of the fluidic oscillator during one cycle of oscillations. These strong transverse oscillations are the result of the Coanda effect with flow leaning towards one wall or the other in a periodic way. The instability starts with any small disturbance causing an asymmetrical pressure difference in the main chamber of the oscillator. After that, part of the flow moves back to the input of the device ($t_1$), then pushes away the main flow ($t_2$). Then the process is repeated on the other side of the device ($t_3 - t_4$) leading to this global instability. Figure 4 shows the time-averaged streamwise velocity field as well as the streamwise and transverse velocity fluctuations. As expected, the oscillator jet, moving from side to side, provides a wide opening angle $\sim 91^\circ$. This feature is well recognized to enhance the efficiency of the mixing process.

Figure 3. The streamwise velocity field for $N = 4$ and $Re_d = 3000$ in $x-y$ plane at $z/d = 0$ during one cycle of oscillations with $\Delta t U_0 / d = 55$.

Figure 5 shows the instantaneous isosurface of $\frac{1}{2}(u_i^2 - u_i u_j) = 2$ [13] for cases $N=6$ and $N=8$. It can be seen, the case $N = 6$ fails to predict the turbulence structures due to the lack of spatial resolutions, whereas the case $N = 8$ is able to capture these structures properly. An accurate prediction of these typical vortices is particularly important when the effectiveness of sweeping jets is assessed for separation control applications.

Figure 4. The time-averaged streamwise velocity (left), streamwise (middle) and transverse (right) velocity fluctuations for $N = 8$ and $Re_d = 3000$ in $x-y$ plane at $z/d = 0$. Dashed black lines on the left denote cross-sections shown in figure 5 (right).

Figure 6 (left) shows the oscillation frequency $f$ as a function of the Reynolds number. The non-dimensional value $St = f d / U_0 \approx 0.017$ appears almost constant over a wide range of $Re_d$ with a slight increase at low $Re_d < 5000$. The numerical results are in excellent agreement with experiments [7] even though only the coarse mesh simulations are performed so far. Figure 6 (right) shows several profiles of the time-averaged streamwise velocity field inside and outside the device. Inside the oscillator there are two relatively intensive recirculating zones in the mean which are the reason of a high pressure difference inside the device. Outside very close to the nozzle the velocity profile appears
to be very wide reflecting excellent mixing properties of the configuration as noted earlier. As expected, the oscillator jet expands in the $y$ direction.

**Figure 5.** Isosurface of nondimensional $Q = 2$ colored with streamwise velocity $u_x$.

**Figure 6.** The non-dimensional oscillation frequency $St = f d/U_0$ of the jet as a function of $Re_d$ (left) and several profiles of the time-averaged streamwise velocity at $x/d = 18.5, 19.5, 20.5, 24.5, 25.5$, $z/d = 0$, $N=8$ and $Re_f=3000$.

**Conclusions**

We studied a turbulent jet generated by a fluidic oscillator using Large-eddy simulations in a range of Reynolds numbers $Re_d = 3000 \rightarrow 30000$. The device represents Φ-shaped configuration providing a strongly unsteady flow due to periodic oscillations based on the Coanda effect. The comparison with experiments [7] showed an excellent agreement in terms of the oscillation frequency in the whole range of $Re_d$.

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