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Effect of upstream turbulence on single and dual-stream jets. Assessment of Zonal Detached Eddy Simulation (ZDES).

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Abstract This paper aims at investigating the effect of upstream turbulence (for instance coming from the engine's internal geometry) on the jet flow development. Simulations are performed using ZDES [1] combined with synthetic turbulence generation methods. Two cases are studied: an incompressible, single-stream jet and a compressible dual-stream one. It is shown that the upstream turbulence reduces the RANS-to-LES transition and improves the prediction of the location of the shock-cells and global jet flow development, which advocates a systematic consideration of realistic nozzle exit conditions in eddy-resolving simulations.

1. Introduction

Hybrid simulations, and more generally eddy-resolving ones, are now widely used in the aeronautic industry [2]. The commonly used RANS/LES approaches (switching from RANS in attached areas to LES in detached ones) rely on the natural flow instabilities to trigger the development of the resolved turbulence in shear layers. These instabilities are rather weak in the case of jet flows, which leads to large delays in the RANS-to-LES transition and poor aerodynamic and aeroacoustic predictions. Some improvements of DES formulation have been proposed to mitigate this delay [1] [3].

Another issue related to the use of eddy-resolving simulations for jet flows is the consideration of freestream turbulence in the jets core, which is inevitable in experiments and comes from the upstream parts of the engine in flight configurations. Few published studies have tackled this issue with different methods [4] [5] [6]. It is noteworthy that, in all these cases, the introduction of upstream turbulence also improved the RANS-to-LES transition.

Therefore, the objective of this paper is to investigate the effect of adding freestream turbulence targeted at reproducing realistic inflow conditions on the turbulence development in mixing layers within the framework of ZDES simulations of jets. This is assessed on two configurations: a single stream, low speed jet and a more realistic dual-stream nozzle at high Reynolds number.

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2. Zonal Detached Eddy Simulation (ZDES)

In this paper, hybrid RANS/LES simulations are performed using the Zonal Detached Eddy Simulation (ZDES) [1]. Modes 1 and 2 of the ZDES are used. The ZDES mode 1, introduced to treat separations triggered by the geometry, relies on a user-defined zonal decomposition of the computational domain in RANS and DES areas. The hybrid length scale $\tilde{d}_{ZDES}^I$ used for the Spalart-Allmaras (SA) model is equal to:

$$\tilde{d}_{ZDES}^I = \begin{cases} d_{wall} & \text{in RANS areas} \\ \min(d_{wall}, C_{DES} \tilde{\Delta}_{ZDES}^I) & \text{in DES areas} \end{cases} \quad (1)$$

where d_{wall} is the wall distance; C_{DES} is the original DES97 constant [7] and $\tilde{\Delta}_{ZDES}^I = \Delta_{vol} = (\Delta x \Delta y \Delta z)^{1/3}$ or $\tilde{\Delta}_{ZDES}^I = \Delta_\omega = \sqrt{\bar{S}_\omega}$, $\bar{S}_\omega$ is the average cross section of the cell normal to the vorticity vector ω . In the present study, the subgrid length scale based on the local vorticity vector direction Δ_ω was chosen since there is a preferred mean vorticity direction. Furthermore, the near-wall functions of the SA model are removed in LES areas for mode 1: $f_{v1}=1$, $f_{v2}=0$, $f_w=0$.

The ZDES mode 2 was developed to deal with separations over smooth surfaces and works as a global approach where the model itself defines the RANS and DES areas, which makes the treatment of complex geometries straightforward for the user. To ensure that attached boundary layers are treated in RANS whatever the grid density, a shielding function f_d is used – similar to the one employed in DDES [8] – to shield the attached boundary layers. The hybrid length scale reads:

$$\tilde{d}_{ZDES}^{II} = d_{wall} - f_d \max(0, d_{wall} - C_{DES} \tilde{\Delta}_{ZDES}^{II}) \quad (2)$$

Conversely to DDES, the mode 2 of ZDES provides a specific definition of the subgrid length scale according to the flow resolution and a threshold value $f_d = 0.8$ determined in Ref [1]. When $f_d < f_{d0}$, $\tilde{\Delta}_{ZDES}^{II} = \Delta_{max}$ (Δ_{max} being the characteristic mesh length necessary to ensure the correct behavior of f_d). When $f_d > f_{d0}$, the subgrid length scale revolves to $\tilde{\Delta}_{ZDES}^{II} = \Delta_\omega$ or Δ_{vol} . As explained in Ref [1], the near-wall functions of the SA model are not modified in mode 2 of ZDES.

3. Single stream jet

3.1 Description of the test case and simulations

The round jet investigated is similar to one investigated experimentally in Ref. [9]. The Reynolds number based on the nozzle exit velocity $U_0 = 20$ m/s and diameter $D = 0.15$ m is equal to $Re_D = 2.1 \cdot 10^5$. During the experiments, the boundary layer inside the nozzle was tripped using sand paper so that the exit boundary layer is fully turbulent, of thickness $\delta_0 = 3$ mm = $0.02 D$ and momentum thickness $\theta_0 = 0.36$ mm = $0.0024 D$.

Fig. 1 Single stream jet case, computational domain

The simulations were performed with the elsA software developed at ONERA [10] which solves the compressible Navier-Stokes equations on structured multi-block meshes. A sketch of the computational domain and boundary conditions is presented in Fig. 1. 40 grid points are used to discretize the nozzle boundary layer, 360 points are used in the azimuthal direction and the mesh contains $40 \cdot 10^6$ cells in total.

The time integration is performed using an implicit LU-SSOR algorithm and a second-order accurate backward Gear scheme with 5 Newton sub-iterations to ensure a drop of one order of magnitude of the inner-iteration residuals.

The diffusive fluxes are discretized using a second-order-accurate centered scheme. The convective terms are treated with the hybrid centered/upwind second-order-accurate AUSM+P scheme [11] using MUSCL extrapolation of the third order.

To generate a realistic turbulent inflow content, the Synthetic Eddy Method (SEM) [12] is used. The SEM is based on the generation of velocity fluctuations carried by synthetic eddies which are superimposed to a target mean flow to obtain a synthetic unsteady turbulent field used to feed an inlet boundary condition.

The formulation relies on the prescription by the user of a target Reynolds stress tensor, which is related here to the jet core turbulence rate Tu : $\overline{u_i u_j} = Tu^2 \times U_0^2 \times \delta_{ij}$ (where U_0 is the inlet mean velocity and δ_{ij} is the Kronecker delta). The values tested for the turbulence length scale σ are given in Table 1.

For all simulations, the time step is $2 \cdot 10^{-6}$ s. The unsteady results are time averaged over 200 ms (~ 25 D/U) after a transient stage estimated of around 120 ms (~ 16 D/U).

Case	RANS/LES approach	Inflow condition
ZDES2	ZDES (all domains : mode 2 Δ_ω)	Steady uniform Pt, Tt
ZDES2-SEM	ZDES (all domains : mode 2 Δ_ω)	SEM Jarrin $\sigma=0,02$ $Tu=7,5\%$
ZDES2-SEM2	ZDES (all domains : mode 2 Δ_ω)	SEM Jarrin $\sigma=0,02$ $Tu=35\%$
ZDES2-SEM3	ZDES (all domains : mode 2 Δ_ω)	SEM Jarrin $\sigma=0,05$ $Tu=7,5\%$

Table 1 Simulations performed for the single-stream jet case

3.2 Results

In this paper, the focus is put on the major modifications in the jet development induced by the introduction of upstream turbulence. A more complete analysis and validation of these results as well as the comparison between mode 1 and 2 of ZDES and DDES is presented in Ref [5].

The shape and size of the injected eddies in the nozzle inlet plane of simulation ZDES2-SEM can be deduced from Fig. 2 (b), to be compared with the uniform inlet in simulation ZDES2. The insets in Fig. 2 depict the turbulence development in the early shear layer. The spatial wavelength and transition length seem to be modified by the upstream turbulence.

Fig. 2 Illustration of the simulations and close-up on the mixing layer early development

More quantitatively, the RMS profiles along the lip line in Fig. 3 show that the dual-peaked shape characteristic of vortex pairing is attenuated. This is attributed

to a reduction of the RANS-to-LES transition length when upstream turbulence is introduced in the jet core, due to the penetration of resolved fluctuations into the nozzle boundary layer treated in RANS which promotes the development of LES content in the early stage of the mixing layer development. The attenuation of the vortex pairing is further evidenced by the velocity spectra in Fig. 4 near the nozzle exit, since the hump near $St_0 = 0.013$ associated with the vortex pairing is smoothed in cases with upstream turbulence.

Fig. 3 Evolution of shear stresses along the lip line

Fig. 4 Velocity spectra close to the nozzle exit

The effect of upstream turbulence on the jet flow development is presented in Fig. 5. The turbulence rate at the nozzle exit in simulation ZDES2-SEM is low but comparable to the one in the experiments, and this seems to improve the potential core length prediction compared to the simulation ZDES2 with zero turbulence rate. The increase of the turbulence rate in the simulations results in a shorter jet (ZDES2-SEM2). When larger synthetic eddies are injected (ZDES2-SEM3 compared to ZDES2-SEM with the same inlet turbulence rate), they are less dissipated by the grid in the nozzle, thus a higher turbulence rate is achieved at the nozzle exit and the jet is slightly shorter. Velocity spectra along the jet centerline in Fig. 6 show the progressive attenuation of the jet column mode at $St_D = 0.6$ when the turbulence rate is increased.

Fig. 5 Evolution of the mean velocity and RMS of velocity along the jet centerline

Fig. 6 Velocity spectra along the jet centerline

4. Dual-stream jet

4.1 Description of the test case and simulations

Fig. 7 Martel test case and measurement lines

The dual-stream jet considered in this paper is the MARTEL configuration which was investigated experimentally at the Pprime institute in Poitiers, France. This configuration is illustrated in Fig. 7 and consists in an isolated heated axisymmetric coaxial jet, without external flow. The details of the operating point computed are given in Ref [13].

The simulations were carried out with the elsA software [10] on a structured multi-block grid of around 205 million grid points (illustrated in Fig. 8), with 416 points in the azimuthal direction. In the mixing layers, the radial spacing is about $\Delta r = \delta\omega/40$, and the axial and azimuthal spacings verify $\Delta x, z < \delta\omega/2$, where $\delta\omega$ is the shear layers vorticity thickness extracted from a preliminary RANS computation.

Fig. 8 ZDES grid and inlet boundary conditions for the Martel test case

The time integration is identical to the one used in the previous section (see section 3.1). The convective fluxes are treated with the centered second order scheme of Jameson with second and fourth order dissipation coefficients equal to $\chi_2 = 0.5$ and $\chi_4 = 0.008$.

In order to introduce upstream turbulence, the Random Flow Generation (RFG) technique developed by Smirnov et al. [14] is used at the nozzle internal ducts inflow boundary conditions (see Fig. 8). This method is based on the superposition of harmonic functions and has already been used in elsA simulations in previous work [4] [15]. The parameters investigated in this paper are given in Table 2, the same parameters are used for both primary and secondary duct inlets. The target

Reynolds stress tensor is related to the turbulence rate by $\overline{u_i u_j} = Tu^2 \times U_0^2 \times \delta_{ij}$, where U_0 is the mean velocity at the inlet of the duct considered.

The physical time step used for unsteady simulations is $\Delta t = 1.5 \cdot 10^{-7}$ s. The spectral analysis has been carried out using a time signal of $T = 36$ ms = 116 D/U, where D is the bypass exhaust diameter and U is the bypass exhaust velocity.

Simulation	J ω	J ω -T10-H/10	J ω -T5-H/10	J ω -T5-H/5
Turbulence rate	-	10%	5%	5%
Turbulent length scale	-	H/10	H/10	H/5

Table 2 Simulations performed for the Martel test case. H is the height of the duct considered

4.2 Results

Fig. 9 illustrates the salient features of the baseline J ω simulation. The reader is referred to Ref [13] for a detailed validation and analysis of this simulation. The secondary mixing layer is quickly destabilized, whereas the primary one seems to suffer from a delay in the RANS-to-LES transition which may be due to the low velocity difference between the primary and secondary streams [13]. In the secondary stream, a shock-cell patterns is observed.

Fig. 9 Main features of the Jw simulation

The evolution of the injected turbulence in the nozzle ducts is depicted in Fig. 10. The intensity and size of the velocity field distortions are correlated with the RFG parameters and no major damping of the fluctuations is observed as they are transported within the ducts.

Fig. 10 Radial velocity fields

The RANS-to-LES transition in the secondary mixing layer can be assessed in Fig. 11. As observed in the results for the single-stream jet, secondary peaks in the profiles of turbulent kinetic energy are somewhat smoothed when upstream turbulence is introduced – even if the main peak is stronger, which suggests a more intense transition. The quicker RANS-to-LES transition leads to a better agreement between the simulations and the experiment regarding the mixing layer growth rate.

Fig. 11 Fan mixing layer streamwise evolution

The azimuthal distributions of vorticity in the jet cross plane at $x/D = 1$ presented in Fig. 12 indicate the level of resolved turbulence outside the mixing layers in both streams. This results in increased mixing in the streams core, which in turns modifies the shock-cell positioning as shown in Fig. 13 and reduces the phase-lag between simulations and experiments. This is a major improvement in the simulations and shows the necessity of taking into account upstream turbulence for a quantitative jets aerodynamic performances prediction.

Fig. 12 Vorticity magnitude in cross plane $x/D=1$

Fig. 13 Time-averaged streamwise velocity in the fan and core streams (red lines in Fig. 7)

5. Summary and conclusion

In both cases investigated in this paper, the introduction of upstream turbulence at the nozzle inlet in the jets core has led to improved agreement with the experimental data with regards to:

- (1) The jet flow development, in terms of potential core length and shock-cell location, thanks to a better reproduction in the simulations of the experimental aerodynamic conditions;
- (2) The RANS-to-LES transition in the shear layers, which is partly attributed to the penetration of the injected fluctuations inside the nozzle boundary layers which promotes the development of LES content in the shear layer. Of interest, it was not observed that this behavior impaired the shielding of the attached boundary layers treated in RANS mode with the ZDES mode 2 (which provides a RANS/LES switch without any user intervention).

Therefore these results promote a systematic introduction of upstream turbulence in eddy-resolving simulations of jets, and emphasize the need for more detailed experimental data on this matter. However, only aerodynamic data has been analyzed so far. Future work will be devoted to the assessment of the jet noise modification due to the upstream turbulence rate.

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