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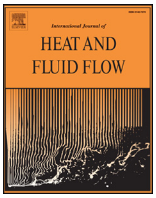

Investigation of turbulence development in incompressible jets with zonal detached eddy simulation (ZDES) and synthetic turbulent inflow

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ABSTRACT

Hybrid RANS/LES simulations of two incompressible jets are performed with the Zonal Detached Eddy Simulation (ZDES). Two functioning modes of the ZDES for the selection of RANS and DES areas are evaluated, namely the user-defined mode (mode 1) and the global- or automatic- mode (mode 2). The RANS-to-LES transition occurs quickly downstream of the nozzle exit and is found to involve the same physics as a laminar to turbulent transition with vortex pairing near the nozzle exit. The effect of the delay in the RANS-to-LES transition on the jet flow development is analyzed. In particular, the delay in the formation of small-scale turbulent structures results in too high turbulence levels in the mixing layers. Furthermore, it is shown, for two cases, that the injection of synthetic turbulence at the nozzle inlet, originally targeted at reproducing the experimental turbulence level in the jet core, has a significant impact on the mixing layer as it accelerates the RANS-to-LES transition, reduces the spatial wavelength of the vortex pairing and promotes the production of fine-scale turbulence which leads to a better agreement with experiments.

1. Introduction

Hybrid RANS/LES simulations of detached and free shear flows are increasingly used for industrial purposes as they present an acceptable trade-off between computational cost and physical accuracy (Deck et al., 2014, Spalart et al., 1997). Within the range of applications of interest, jet flows are very challenging since they involve several multidisciplinary aspects. Hybrid simulations, and more generally eddy-resolving ones, have therefore been widely used for instance for jets aerodynamics (Verrière et al., 2016, DeBonis, 2010, Mahak et al., 2014), thermal problems (Brunet, 2012, Zuckerman and Lior, 2006), and acoustics (Bogey et al., 2012, Xia et al., 2012, Eastwood et al., 2012, Shur et al., 2006, Tyacke et al., 2016). The major issue for hybrid simulations of such flows is that the most commonly used approaches rely on the natural flow instabilities to trigger the development of the resolved turbulence in shear layers (from RANS in attached areas to LES in detached ones). This is the basic principle of the Detached Eddy Simulation (DES) (Spalart et al., 1997) and its subsequent variations and improvements (Spalart et al., 2006, Shur et al., 2008, Shur et al., 2015, Deck, 2012), which have proved to be very efficient for massively separated flows where strong instabilities occur (Deck et al., 2014).

However, jet flows are not governed by large-scale instabilities; therefore the RANS-to-LES transition can suffer from a delay which is sometimes referred to as the "grey area" issue. The most obvious technique to suppress the delay would be to resolve the attached boundary layer inside the nozzle, at least partly using Wall Modeled LES. This is done for instance for an axisymmetric jet in Brès et al. (2015) and shows very good results but does not seem applicable nor robust enough for complex geometries due to computational costs and implementation issues of turbulence generation methods for boundary layers on curvilinear grids. In the framework of global RANS/LES approaches (global in the sense that the model decides whether the local resolution should be RANS or LES, which is the most relevant approach for industrial applications) several proposals have been made to mitigate the RANS-to-LES transition length. Significant improvements have been achieved by optimizing the hybrid length scale so that the RANS eddy viscosity is removed in LES regions to avoid dampening the instabilities without compromising the safe treatment of the attached boundary layers (Shur et al., 2015, Deck, 2012, Kok and van der Ven, 2010, Kok and van der Ven, 2012). Another option is to improve the subgrid scale model in the LES areas, which has been tested in Mockett et al. (2015).

The RANS-to-LES transition in jet flows simulations is all the more critical since the jet flow development and radiated noise are strongly influenced by the initial state of the mixing layer. This topic has been widely investigated, both experimentally and

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Nomenclature

D	Nozzle exit diameter
δ	Boundary layer thickness
θ	Momentum thickness
Δ_ω	Length scale based on the vorticity
$\Delta_{\max}$	Length scale based on the maximum grid spacing

numerically. Initially laminar or transitional mixing layers are characterized by vortex parings at a reduced frequency based on the initial momentum thickness and jet velocity $St_\theta = 0.012$ ("shear layer mode") (Bogey and Bailly, 2010, Bogey et al., 2012, Kim and Choi, 2009, Zaman and Hussain, 1980, Zaman, 1985). These instabilities have significant consequences on the radiated noise and its spectral distribution (Bogey et al., 2012, Zaman, 1985). Besides, when the initial boundary layer is fully turbulent, the potential core is longer (Hussain and Zedan, 1978, Bogey et al., 2012).

Another issue for jets simulations is the reproduction of inflow conditions at the nozzle inlet. In a steady framework, mass flow, total pressure and temperature have been shown to have a strong influence on the jet structure (Verrière et al., 2014) and are carefully controlled both experimentally and numerically. To go further into the accurate reproduction of flight and wind-tunnel conditions, the question of the turbulent rate in the jets core arises all the more since unsteady simulations are more and more used. To this effect, one can take advantage of turbulent inflow conditions which have been mostly developed in the framework on LES initialization for wall bounded flows, for instance (Smirnov et al., 2001, Jarrin et al., 2009). Besides, it seems that the residual turbulence in jets core is less challenging to generate than wall turbulence since it involves less anisotropy and turbulent scales variety. Some applications of the use of synthetic turbulent boundary conditions to reproduce jets core turbulent rate have shown promising results (Kim and Choi, 2009, Brunet, 2012) (Gand et al., 2015). In the same spirit, some work has been done to add upstream turbulence coming from the fan in jets simulations (Tyacke et al., 2016). Of interest, it is observed in these applications that the introduction of freestream turbulence in the jets core not only improves the overall realism of the computations but also has a significant impact on the RANS to LES transition in the mixing layer.

The objective of this article is therefore 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. The article is organized as follows. First, the numerical methods for turbulence modeling and freestream turbulence generation are presented. Two configurations of axisymmetric incompressible jets are then investigated: the first one with a thin initial boundary layer, the second one originating from a fully developed channel flow.

2. Numerical methods

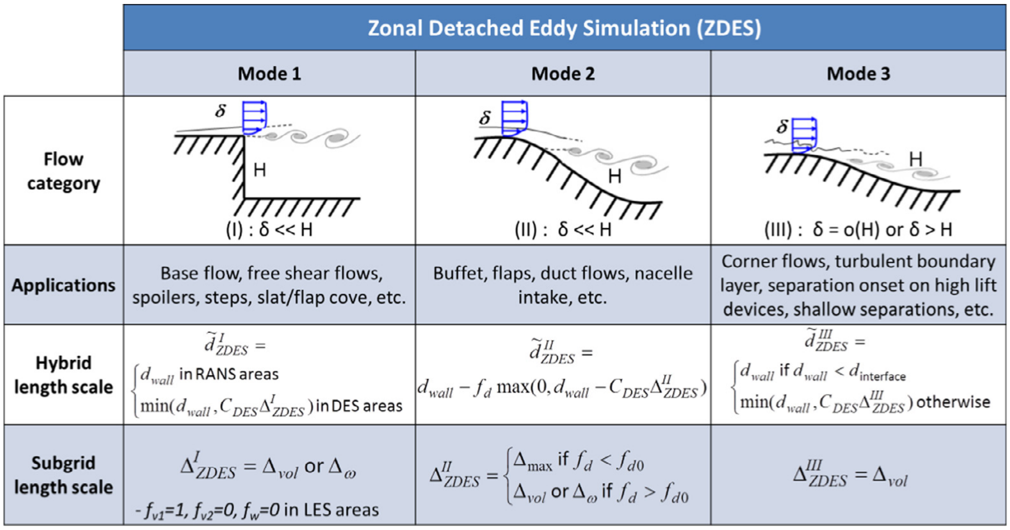
2.1. Zonal detached eddy simulation

The approach used in this work is the Zonal Detached Eddy Simulation (ZDES) (Deck, 2012) developed at ONERA. As mentioned in the introduction, this approach has been used with success to simulate a wide range of applications of industrial interest (Deck et al., 2014). One of the advantages of the ZDES is its flexibility illustrated in Fig. 1, which shows that ZDES covers several types of detached flows, which can be combined. In the present study, modes 1 and 2 of the ZDES are used. Mode 3, devoted to WMLES, is beyond the scope of this work. An example of the combined use of the three modes of ZDES within the same computation can be found in Deck and Laraufie (2013).

The ZDES is based on the basic idea of the original Detached Eddy Simulation (Spalart et al., 1997) (DES97) which relies on the Spalart–Allmaras (SA) RANS model (Spalart and Allmaras, 1994). A brief description of the SA model is provided below, the reader is referred to the original paper (Spalart and Allmaras, 1994) for a full description. The SA model is based on the transport equation of a pseudo viscosity $\tilde{\nu}$ involving production, diffusion and destruction terms:

$$\frac{D\tilde{\nu}}{Dt} = \underbrace{c_{b1}\tilde{S}\tilde{\nu}}_{production} + \underbrace{\frac{1}{\sigma}\left[\nabla.((\nu+\tilde{\nu})\nabla\tilde{\nu}) + c_{b2}(\nabla\tilde{\nu})^2\right]}_{diffusion} \underbrace{- c_{w1} f_w \left[\frac{\tilde{\nu}}{d_w}\right]^2}_{destruction} \quad (1)$$

where, d_w is the distance to the wall, c_{b1}, c_{b2} and c_{w1} are constants, $\tilde{S}$ is a modified vorticity magnitude involving a near wall function f_{v2} and f_w is another near-wall function. The eddy viscosity entering the Boussinesq closure for the RANS equations is defined using a third near-wall function f_{v1}: $\nu_t = f_{v1}\tilde{\nu}$. The three near-wall corrections f_w, f_{v1} and f_{v2} were calibrated to ensure the correct behavior of $\tilde{\nu}$ in the viscous, buffer, log-layer and outer parts of the boundary layer. The basic principle of DES97 is to



	Zonal Detached Eddy Simulation (ZDES)		
	Mode 1	**Mode 2**	**Mode 3**
Flow category	(I) : δ << H	(II) : δ << H	(III) : δ = o(H) or δ > H
Applications	Base flow, free shear flows, spoilers, steps, slat/flap cove, etc.	Buffet, flaps, duct flows, nacelle intake, etc.	Corner flows, turbulent boundary layer, separation onset on high lift devices, shallow separations, etc.
Hybrid length scale	$\tilde{d}^{I}_{ZDES} = \begin{cases} d_{wall} \text{ in RANS areas} \\ \min(d_{wall}, C_{DES}\Delta^{I}_{ZDES}) \text{ in DES areas} \end{cases}$	$\tilde{d}^{II}_{ZDES} = d_{wall} - f_d \max(0, d_{wall} - C_{DES}\Delta^{II}_{ZDES})$	$\tilde{d}^{III}_{ZDES} = \begin{cases} d_{wall} \text{ if } d_{wall} < d_{\text{interface}} \\ \min(d_{wall}, C_{DES}\Delta^{III}_{ZDES}) \text{ otherwise} \end{cases}$
Subgrid length scale	$\Delta^{I}_{ZDES} = \Delta_{vol}$ or Δ_ω - f_{v1}=1, f_{v2}=0, f_w=0 in LES areas	$\Delta^{II}_{ZDES} = \begin{cases} \Delta_{\max} \text{ if } f_d < f_{d0} \\ \Delta_{vol} \text{ or } \Delta_\omega \text{ if } f_d > f_{d0} \end{cases}$	$\Delta^{III}_{ZDES} = \Delta_{vol}$

Fig. 1. Summary of the ZDES formulation (adapted from Deck et al., 2014).

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