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Numerical investigation on the three-dimensional flow characteristics of unsteady subsonic elliptic jet

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ABSTRACT

Based on large eddy simulation (LES), combined with high order tuned centered-difference (TCD) scheme, the initial flow characteristics of the unsteady subsonic elliptic jet was investigated numerically. The numerical results illustrate the formation, variation and development of the subsonic elliptic jets' initial flow structures. Moreover, the self-induced deformation of the noncircular vortex loops and the distribution of the streamwise vorticity field have been completely clear using the three-dimensional (3D) view. The vorticity field of the results qualitatively shows that the self-induced Biot-Savart deformation of primary vortex loop (PVL) leads to the streamwise vortices generation in the flow, and the streamwise vortex pairs enlarge along the primary vortex core and augment the deformation of PVL. These two mechanisms govern the phenomenon of axis switching. Subsequently, the coherent structures present in the major and minor axis planes of the elliptic vortex loop and jet shear layer are identified with proper orthogonal decomposition (POD) method. Moreover, the mechanisms of vortex dynamics and the entrainment features of various noncircular jets have also been described in detail.

1. Introduction

Relative to those of circular jets, non-circular jets [1], such as elliptic, rectangular, and square jets etc., have been considered as an efficient technique for passive flow control, which attract special attentions due to their enhancing entrainment and mixing properties. The elliptic jet is a special member of the family of non-circular jets, it has no sharp corners, and serves as the intermediate between the two extreme limiting of possible jet shapes (the circular and planar jets) [2,3]. Thus, an elliptic jet may lead the way to the understanding of other non-circular jets.

Previous studies have found that the major flow structure of jet is strongly related to the curvature of the nozzle geometry, aspect ratio (*AR*) and initial momentum thickness distribution [4]. The non-uniform curvature of an elliptic jet causes the initial momentum thickness to vary around the exit perimeter, and the azimuthal curvature of the elliptic vortex structure causes non-uniform self-induction and complex three-dimensional deformation, which results in an enhancement in mixing eventually [2,5]. As the jet spreads, its mean-flow cross-section evolves in such a manner that, after a certain distance from the nozzle, the major and the minor axes is interchanged. This phenomenon is denoted as the axis switching, and has been observed in various noncircular jets [4,6-15]. Moreover, Tsuchiya et al. [16] showed that the axial turbulence component along the jet's axis increases faster for large aspect ratio in the orifice elliptic jet, and the distance of the crossover location from the nozzle was directly propotional to the nozzle aspect-ratio. A similar trend in an investigation on the effect of *AR* on the development of orifice rectangular jets was reported by Quinn [10].

Hussain and Husain [2] provided an explanation for the axis switching of elliptic jets based on the dynamics of rolled-up azimuthal vortex structures. Later, Quinn's [10] measurements showed the near region of the square jet is dominated by four sets of counter-rotating streamwsie vortices which are inferred also to play a significant role during the axis switching. The important role of streamwise vortices in the entrainment process of a non-circular jet was convincingly demonstrated by Liepmann and Gharib [17]. Grinsterin et al. [7] demonstrated the distortion of the azimuthal vortex structures can lead to streamwise vortices even in the time-averaged flow field by the computational results, and indicated that the dynamic of azimuthal vortex structures and streamwise vortex pairs are not independent of each other. Thus a set of experiments has been conducted in an attempt to shed light onto these processes. The experimental studies of Zaman [13] and Gutmark and Grinstein [1] have identified that in elliptic jets, the underlying mechanism of axis-switching behavior results from self-induced Biot-Savart deformation of vortex rings due to nonuni-

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form azimuthal curvature and interaction between azimuthal and streamwise vorticities. Biot-Savart self-induction causes segments with larger curvatures to move faster than those with smaller curvatures, then the vortex structure cannot retain its original shape and remains in a plane, and eventually results in the 90° axis switching. Based on above experimental conclusions and their experimental results, Zare-Behtash et al. [14,15] depicted experimentaly the phenomenon of axis switching of the elliptic and square vortex loop.

Previous experimental and numerical studies have focused mainly on the flow structures of steady jets, on the other hand, the structures and their evolution of PVLs of unsteady jets or the initial flow fields of steady jets deserve more attention for resolving many problems encountered in propulsion applications [18] and armament launch [19]. In the present study, we aim to present a complete description of the 3D characteristics of the initial flow structures and their evolution of a subsonic elliptic jet with the use of LES method and high resolution tuned centered-difference (TCD) scheme. Our results illustrate the detail evolution of the PVL, in particular, the phenomenon of the deformation of vortex loop and the distribution of the streamwise vorticity field have been displayed and discussed, which provide insight into the underlying mechanisms of the axis switching phenomenon of non-circular vortex loop. The proper orthogonal decomposition (POD) analysis was applied to characterize the dominant modes of the elliptic jet. Moreover, the formation of ribs and the entrainment features of unsteady elliptic jet have also been illustrated in details.

2. Numerical method and physical model

2.1. Numerical method

The three-dimensional LES equations can be obtained by Favre filtering the Navier–Stokes equations in the Cartesian coordinate system [20].

$$\frac{\partial \bar{\rho}}{\partial t}+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j)=0, \tag{1}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_i\tilde{u}_j)=-\frac{\partial \bar{p}\delta_{ij}}{\partial x_i}+\frac{\partial \sigma_{ij}}{\partial x_j}-\frac{\partial \tau_{ij}^{sgs}}{\partial x_j}, \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{E}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{E}+\bar{p})\tilde{u}_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\bar{\kappa}\frac{\partial \tilde{T}}{\partial x_j}\right)+\frac{\partial \sigma_{ij}\tilde{u}_i}{\partial x_j}-\frac{\partial q_j^{T-sgs}}{\partial x_j}, \tag{3}$$

$$\frac{\partial\left(\bar{\rho}\tilde{f}\right)}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_j\tilde{f})}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\bar{\rho}\bar{D}\frac{\partial \tilde{f}}{\partial x_j}-\rho q_j^{f-sgs}\right]. \tag{4}$$

where the filtered Newtonian stress tensor σ_{ij}, pressure $\bar{p}$ and total energy $\bar{\rho}\tilde{E}$ are expressed by

$$\sigma_{ij}=\bar{\mu}\left(\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial \tilde{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial \tilde{u}_k}{\partial x_k}\right),$$

$$\bar{p}=\bar{\rho}R^0\tilde{T}\sum_{m=1}^{2}\frac{\tilde{Y}_m}{W_m}+\bar{\rho}R^0\sum_{m=1}^{2}\frac{T_m^{sgs}}{W_m},$$

$$\bar{\rho}\tilde{E}=\frac{\bar{p}}{(\tilde{\gamma}-1)}+\frac{1}{2}\bar{\rho}(\tilde{u}_k\tilde{u}_k)+\frac{1}{2}\tau_{kk},$$

The subgrid terms including the stress tensor τ_{ij}^{sgs}, turbulent temperature flux q_j^{T-sgs}, scalar transport flux q_j^{f-sgs} and the temperature-species correlation term T_m^{sgs} are given by

$$\tau_{ij}^{sgs}=\bar{\rho}\left(\widetilde{u_iu_j}-\tilde{u}_i\tilde{u}_j\right), \tag{5}$$

$$q_j^{T-sgs}=\bar{\rho}\left(\widetilde{c_pTu_j}-\tilde{c}_p\tilde{T}\tilde{u}_j\right), \tag{6}$$

$$q_j^{f-sgs}=\bar{\rho}\left(\widetilde{fu_j}-\tilde{f}\tilde{u}_j\right), \tag{7}$$

$$T_m^{sgs}=\widetilde{TY_m}-\tilde{T}\tilde{Y}_m \tag{8}$$

The mixture fraction f is defined as: $f==(Y-Y_1)/(Y_2-Y_1)$, where Y_1 refers to the mass fraction of oxidizer (ambient gas), and Y_2 denotes the fuel (jet gas) mass fraction. With this definition, f takes the value 1 in the jet gas and 0 in the ambient air. $\bar{\kappa}$, $\bar{\mu}$ and $\bar{D}$ are the filtered heat conduction, dynamics viscosity and molecular diffusivity, respectively. They are obtained from binary mixing rules and the pure component mixing properties. W_m denotes the molecular weight of component m, R^0 is the gas constant and its value is $R^0==8.3143$ J/(mol·K).

The subgrid terms (5)–(8) need to be modeled for the closure of the multi-component LES equations. We choose the recently developed stretched-vortex subgrid scales (SGS) model for multicomponent, compressible flows to approach the unresolved subgrid terms [21]. The stretched-vortex SGS model which uses stretched vortices to represent the subgrid scales was proposed originally for incompressible flow [22], and has been extended to different purposes [23-25]. The stretched vortex is a physical model for turbulent fine scales which is assumed to be consisted of tube-like structures with concentrated vorticity [26]. The stretched-vortex SGS model is designed for simulating turbulent fine scales and has the capability of predicting subgrid scale quantities systematically. In this model, the subgrid turbulent kinetic energy takes the Lundgren form [26].

The fluid-solver framework AMROC (Adaptive Mesh Refinement in Object-oriented C++++) [27] has been proven to be advantageous for the LES of compressible flows [28], it includes the block-structured adaptive mesh refinement (SAMR) method [29] and a hybrid numerical method of tuned centered difference-weighted essentially non-oscillatory (TCD-WENO) [30] for simulating the compressible flow. SAMR method in AMROC is one kind of adaptive mesh refinement algorithm designed especially for hyperbolic partial differential equations [31]. The computational domain consists of blocks with rectangular grids, and SAMR uses a hierarchical block data structure, therefore each block can be solved as a single grid which makes the computation more effective than other methods. Further information can be found in Ref. [27,29,31].

AMROC provides an object-oriented framework implementation of SAMR method mentioned above, in which the SAMR method has been decoupled from a particular scheme, therefore, different schemes can be chosen for the solving. It characterizes with the efficient parallelization strategy on distributed memory machines and can run on all high-performance computers with MPI-library installed.

The subsonic jet flow is a complex turbulent shear flow, therefore, the spatial and temporal resolution requirement vary largely. Tuned centered-difference (TCD) scheme uses the Ghosal truncation error as an object function, and optimizes the coefficients of center difference template to eliminate the dispersion error, which can perform well in LES simulations for unsteady gas-dynamic flows [30]. In this paper, the derivatives of inviscid fluxes are presently computed using a 7-point tuned centered-difference (TCD) scheme, this leads to 5th order precision. Time advancement is achieved with the fourth-order Runge-Kutta method.

2.2. Physical model

The three-dimensional computational domain and corresponding coordinate system is shown in Fig. 1a. A cuboid is chosen as the computational domain, and the original point of coordinate