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Separation flow control

Coherent structures in the boundary layer of a flat thick plate

Structures cohérentes dans la couche limite d'une plaque plane épaisse

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ABSTRACT

We use POD and EPOD (extended POD) analysis to extract the main features of the flow over a thick flat plate simulated with an LES. Our goal is to better understand the coupling between the velocity field and the surface pressure field. We find that POD modes based on the full velocity and energy fields contain both flapping and shedding frequencies. Pressure modes are found to be uniform in the spanwise direction and the most intense variations take place at the mean reattachment point. Velocity modes educed from the pressure modes with EPOD are seen to correspond to eddies shed by the recirculation bubble.

RÉSUMÉ

On considère l'écoulement au-dessus d'une plaque plane épaisse. Nous utilisons la simulation aux grandes échelles et l'analyse POD/EPOD pour comprendre le couplage entre le champ de vitesse et le champ de pression à la paroi. Les modes POD extraits de la vitesse contiennent des fréquences correspondant aux phénomènes de flapping et de shedding. Les modes de pression sont uniformes dans la direction transverse et les variations les plus intenses sont observées au point de réattachement. Les modes de vitesse construits à partir des modes de pression avec l'approche EPOD correspondent à des tourbillons associés à la bulle de recirculation.

1. Introduction

Aerodynamics of vehicles are characterized by the physics of massively separated flows. Kiya and Sasaki [1] showed that the flow in the separation zone is governed by two mechanisms: the shedding of large-scale vortices and a low-frequency unsteadiness called "flapping". The connection between these two mechanisms is still not clear. Another connection that needs to be elucidated is the relationship between the velocity dynamics and the pressure fluctuations. Understanding this coupling represents a challenge for the control of acoustic disturbances. The present paper builds on the results obtained by Tenaud et al. [2] for the LES of the flow over a thick flat plate. We apply POD analysis and EPOD (extended POD) analysis to their numerical data in order to determine the salient features of the pressure and velocity field.

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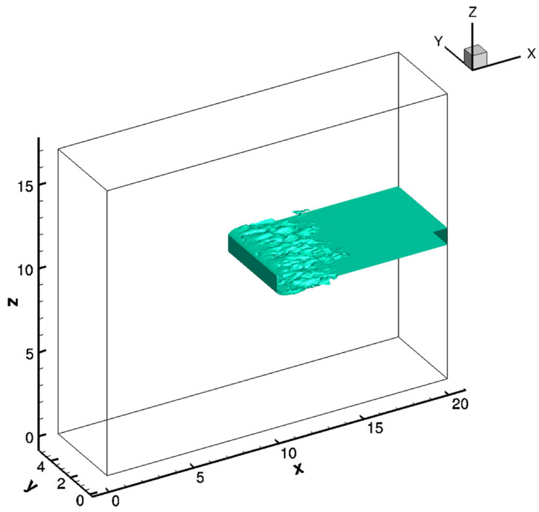

Fig. 1. (Color online) Isosurface of zero streamwise velocity – the arrow indicates the flow direction.

2. The numerical method

We consider the flow over a flat thick plate of thickness H and length L. The total dimensions of the plate in the simulation are $L_x, L_z = (25, 17)H$. The portion of the domain used for POD analysis, which excludes the downstream part of the plate $x > 20H$, is represented in Fig. 1. The height of the numerical domain is $5H$. The Reynolds number based on the constant velocity imposed at the upstream boundary-located at a distance $10H$ from the leading edge of the plate and the plate thickness is $R = 7500$.

The equations of motion are those for a compressible flow. We consider air with a constant specific heat ratio $\gamma = 1.4$. The Prandtl number is taken to be $Pr = 0.73$. The equations are solved using an LES approach. Results reported here were obtained with a dynamic viscosity model [3]. A high-order coupled scheme in time and space was implemented in the parallel code CHORUS. More details can be found in [2].

3. POD analysis

3.1. The POD technique

POD is a statistical technique [4] which extracts the most energetic motions of the flow. Any physical quantity $\underline{q}(\underline{x}, t)$ (which can be the velocity field, density, or any combination thereof) can be written as

$$\underline{q}(\underline{x}, t) = \sum_{n \geq 1} (\lambda^n)^{1/2} a^n(t) \underline{\phi}_q^n(\underline{x}) \tag{1}$$

where

- the spatial mode $\underline{\phi}_q^n$ is the n-th eigenvector of the eigenproblem

$$\int \langle \underline{q}(\underline{x}, t) \underline{q}(\underline{x}', t) \rangle \underline{\phi}_q^n(\underline{x}') \, \mathrm{d}\underline{x}' = \lambda^n \underline{\phi}_q^n(\underline{x}) \tag{2}$$

  where $\langle \underline{q}(\underline{x}, t) \underline{q}(x', t) \rangle$ is the time-averaged spatial autocorrelation tensor of the quantity $\underline{q}$. By construction the eigenvectors $\underline{\phi}_q$ constitute an orthonormal family;
- λ^n represents the energy of the n-th mode, with $\lambda^1 \geq \lambda^2 \geq \ldots$;
- the temporal coefficient $a^n(t)$ represents the amplitude of the n-th mode and is also normalized to be 1. By construction the coefficients are uncorrelated with each other.

If the autocorrelation tensor is constructed from N selected snapshots of the flow at instants t^k, it can be shown [5] that

$$\underline{\phi}_q^n(\underline{x}) = \sum_{k=1}^{N} (\lambda^n)^{1/2} a^n(t^k) \underline{q}(\underline{x}, t^k) \tag{3}$$