C. R. Mecanique 345 (2017) 378–385

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Optimal streaks in the wake of a blunt-based axisymmetric bluff body and their influence on vortex shedding

Mathieu Marant [a], Carlo Cossu [a], Grégory Pujals [b]

[a] *Institut de mécanique des fluides de Toulouse, CNRS–INP–UPS, 2, allée du Professeur-Camille-Soula, 31400 Toulouse, France*
[b] *PSA Peugeot Citroën, Centre technique de Vélizy, 2, route de Gisy, 78943 Vélizy-Villacoublay cedex, France*

A R T I C L E   I N F O

Article history:
Received 3 February 2017
Accepted 11 May 2017
Available online 7 June 2017

Keywords:
Fluid dynamics
Hydrodynamic stability
Flow control

A B S T R A C T

We compute the optimal perturbations of azimuthal wavenumber m THAT maximize the spatial energy growth in the wake of a blunt-based axisymmetric bluff body. Optimal perturbations with $m \neq 0$ lead to the amplification of streamwise streaks in the wake. When forced with finite amplitude $m \neq 1$, optimal perturbations have a stabilizing effect on large-scale unsteady vortex shedding in the wake. We show that $m \geq 2$ modes, which are forced with zero mass flux, can significantly reduce the amplitude of the unsteady lift force exerted on the body. When combined with low levels of base bleed, these perturbations can completely suppress the unsteadiness in the wake with reduced levels of mass injection in the flow.

1. Introduction

Suitable three-dimensional perturbations applied to nominally two-dimensional basic flows are known to be able to weaken and even suppress vortex shedding in the wake of bluff bodies (see, e.g., [1,2] and [3] for a review). It has recently been shown that this stabilizing action is associated with the quenching of the local absolute instability in the wake [4,5], leading to the stabilization of the associated global mode [6,7].

In the case of 3D control of 2D wakes, the role of the stabilizing perturbations is essentially to force spanwise periodic perturbations of the streamwise velocity in the wake. In the literature pertaining to wall-bounded shear flows, these spanwise periodic perturbations of the streamwise velocity are known as 'streamwise streaks' and they are known to be very efficiently forced by streamwise vortices through the lift-up effect (see, e.g., [8,9] for a review). The shape of the optimal forcing leading to the maximally amplified streaks can be computed through standard optimization techniques and is associated with large energy amplifications of the forcing, whose maximal value typically increases with the Reynolds number. Such an optimization has been recently performed on parallel and non-parallel model wakes [5,6] and on the circular cylinder wake [7], showing that the efficiency of the 3D control of 2D wakes can be greatly improved by forcing the streaks optimally. In the case of the cylinder 2D wake, it is found that the optimal spanwise wavelengths leading to the most amplified streaks in the wake almost coincide with the ones that are the most efficient to quench vortex shedding [7].

While important progress has been achieved in the case of the 3D control of nominally 2D wakes, the same is not true in the case of three-dimensional wakes, which are the most relevant to many applications (see, e.g., [10] for a discussion of this issue in the context of the aerodynamics of heavy vehicles). The scope of the present study is therefore to test

E-mail address: carlo.cossu@imft.fr (C. Cossu).

http://dx.doi.org/10.1016/j.crme.2017.05.010

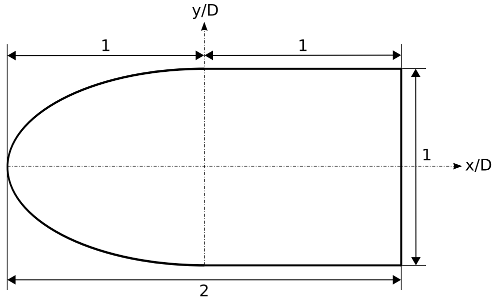

Fig. 1. Longitudinal section of the axisymmetric blunt-based cylinder of diameter D with axis x parallel to the free-stream velocity. The blunt nose of the cylinder is a half-ellipsoid of circular cross-section (diameter D) and longitudinal half-axis of length D extending from $x/D = -1$ to $x/D = 0$. The tubular body has a diameter D and extends from $x/D = 0$ to $x/D = 1$.

the effectiveness of an extension to 3D wakes of the approach used for 2D wakes. We choose as a testbed the wake of a blunt-based axisymmetric bluff body with an ellipsoidal nose and a square back whose global stability has been previously investigated [11]. For this configuration, it has been found that the sequence of global instabilities developing in the wake is similar to the one observed for a sphere and in other axisymmetric wakes with a first steady instability of the axisymmetric wake that breaks the axisymmetry by giving rise to a non-zero steady lift force. This primary state then undergoes a (secondary) instability leading to unsteadiness in the wake and to an unsteady lift force on the body. It has also been shown that for the considered configuration these global instabilities can be stabilized with base bleed [11]. Our approach, similarly to previous investigations [5–7,12–15], consists in first computing the steady, azimuthally ('spanwise') periodic optimal perturbations inducing the maximum growth of streaks in the wake and then study their stabilizing effect on the wake unsteadiness. We anticipate that the found $m \neq 1$ optimal perturbations have a stabilizing effect on the global instabilities.

The mathematical formulation of the problem is introduced in §2. The computed optimal energy amplifications and the associated perturbations as well as the analysis of their stabilizing effect are presented in §3. These results are further discussed in §4 where some conclusions are also drawn.

2. Problem formulation

We consider the flow of an incompressible viscous fluid of density ρ and kinematic viscosity ν past an axisymmetric blunt-based cylinder of diameter D and total length $L = 2D$ whose axis is parallel to the free-stream velocity $U_\infty \mathbf{e}_x$ (where $\mathbf{e}_x$ is the unit vector oriented parallel to the axis x of the cylinder). The blunt nose of the cylinder is an ellipsoid with circular cross-section of diameter D and longitudinal half-axis with 2:1 ratio. The tubular body has a diameter D and a length D (see Fig. 1). In dimensionless coordinates based on D, therefore, the nose of the body extends from $x = -1$ to $x = 0$, the tubular body from $x = 0$ to $x = 1$, and the wake occupies the region $x > 1$.

The flow is governed by the Navier–Stokes equations for an incompressible viscous fluid:

$$\nabla \cdot \mathbf{u} = 0, \qquad \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} \tag{1}$$

where $\mathbf{u}$ and p and the dimensionless velocity and pressure fields and $Re = U_\infty D/\nu$ is the Reynolds number. The velocity, pressure, lengths and times have been made dimensionless with U_∞, ρU_∞^2, D and D/U_∞ respectively. Homogeneous boundary conditions for the velocity are enforced on the body surface except in the controlled case where wall-normal control velocities are enforced.

In the first part of the study, we compute the linear optimal spatial perturbations of the steady axisymmetric solution to the Navier–Stokes equations $\mathbf{U}_0$, which is linearly stable for sufficiently low Reynolds numbers. These perturbations satisfy the Navier–Stokes equations rewritten in perturbation form:

$$\nabla \cdot \mathbf{u}' = 0, \qquad \frac{\partial \mathbf{u}'}{\partial t} + \mathbf{u}' \cdot \nabla \mathbf{U} + \mathbf{U} \cdot \nabla \mathbf{u}' + \mathbf{u}' \cdot \nabla \mathbf{u}' = -\nabla p' + \frac{1}{Re} \nabla^2 \mathbf{u}' \tag{2}$$

where $\mathbf{U} = \mathbf{U}_0$ and the nonlinear term $\mathbf{u}' \cdot \nabla \mathbf{u}'$ is neglected for the computation of the linear optimal perturbations. In the following, steady perturbations $\mathbf{u}'$ are considered, which are of particular interest in open-loop flow control applications and which are forced by radial blowing or suction $u'_{\mathrm{w}}(\theta, x)\mathbf{e}_r$ enforced on the body lateral surface ($0 < x/D < 1$, $r/D = 1/2$). Similarly to [7], the optimal spatial energy amplification of wall control forcing is defined as $G(x) = \max_{u_{\mathrm{w}}} e'(x)/e'_{\mathrm{w}}$, where e'_{w} is the (input) kinetic energy of the blowing and suction forced on the lateral surface and e' is the (output) local perturbation kinetic energy at the station x respectively defined, in dimensionless coordinates, as $e'_{\mathrm{w}} = (1/4) \int_0^{2\pi} \int_0^1 (u'_{\mathrm{w}})^2 \,\mathrm{d}x \,\mathrm{d}\theta$ and $e'(x) = (1/2) \int_0^{2\pi} \int_0^\infty \mathbf{u}' \cdot \mathbf{u}' \, r \,\mathrm{d}r \,\mathrm{d}\theta$.