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Asymptotic theory of turbulent bluff-body separation: A novel shear layer scaling deduced from an investigation of the unsteady motion

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Abstract

A rational treatment of time-mean separation of a nominally steady turbulent boundary layer from a smooth surface in the limit $\mathrm{Re} \to \infty$, where Re denotes the globally defined Reynolds number, is presented. As a starting point, it is outlined why the "classical" concept of a small streamwise velocity deficit in the main portion of the oncoming boundary layer does not provide an appropriate basis for constructing an asymptotic theory of separation. Amongst others, the suggestion that the separation points on a two-dimensional blunt body is shifted to the rear stagnation point of the impressed potential bulk flow as $\mathrm{Re} \to \infty$—which is expressed in a previous related study—is found to be incompatible with a self-consistent flow description. In order to achieve such a description, a novel scaling of the flow is introduced, which satisfies the necessary requirements for formulating a self-consistent theory of the separation process that distinctly contrasts former investigations of this problem. As a rather fundamental finding, it is demonstrated how the underlying asymptotic splitting of the time-mean flow can be traced back to a minimum of physical assumptions and, to a remarkably large extent, be derived rigorously from the unsteady equations of motion. Furthermore, first analytical and numerical results displaying some essential properties of the local rotational/irrotational interaction process of the separating shear layer with the external inviscid bulk flow are presented.

Keywords: Asymptotics; Coherent motion; Gross separation; Perturbation methods; Turbulent boundary layers; Turbulent shear layers

1. Introduction

The rational description of break-away separation of a statistically steady and two-dimensional incompressible turbulent boundary layer flow past an impermeable rigid and smooth surface in the high-Reynolds-number limit represents a long-standing unsolved hydrodynamical problem. Needless to say that an accurate prediction of the position of separation, in combination with the local behaviour of the skin friction, has great relevance for many

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engineering applications, where e.g. internal flows, like those through diffuser ducts, or flows past airfoils play a crucial role.

1.1. Problem formulation and governing equations

The picture of such flows near separation is sketched in Fig. 1. As a basic assumption, the suitably formed global Reynolds number Re is taken to be asymptotically large:

$$\mathrm{Re} \coloneqq \tilde{U}\tilde{L}/\tilde{\nu} \to \infty, \quad \nu \coloneqq \mathrm{Re}^{-1} \to 0. \tag{1}$$

Herein $\tilde{\nu}$, $\tilde{L}$, and $\tilde{U}$ denote, respectively, the (constant) kinematic viscosity of the fluid, a reference length, typical for the geometry of the portion of the surface under consideration, and a characteristic value of the surface slip velocity impressed by the limiting inviscid stationary and two-dimensional irrotational bulk flow, hereafter formally indicated by $\nu = 0$. All flow quantities are suitably non-dimensionalised with $\tilde{L}$, $\tilde{U}$, and the (uniform) fluid density. Let t, p, $\boldsymbol{x} = (s, n, z)$, and $\boldsymbol{u} = (u, v, w)$ be the time, the fluid pressure, the position, and the velocity vector. Here u, v, and w are the components of $\boldsymbol{u}$ in directions of the natural coordinates s, n, and z, respectively, along, normal to, and projected onto the separating streamline $\mathscr{S}$, given by $n = 0$, of the flow in the limit $\nu = 0$. Furthermore, $u_e(s)$ denotes the surface slip velocity in that limit. The origin $s = n = 0$ is chosen as the location S where $\mathscr{S}$ departs from the surface. Thus, $\mathscr{S}$ coincides with the surface contour for $s \leqslant 0$. Also, note that $\mathscr{S}$ has, in general, a curvature of $\mathcal{O}(1)$ for $|s| = \mathcal{O}(1)$.

In coordinate-free form, the Navier–Stokes equations then are written as

$$\nabla \cdot \boldsymbol{u} = 0, \tag{2}$$

$$\mathrm{D}_t \boldsymbol{u} = -\nabla p + \nu \Delta \boldsymbol{u}, \quad \mathrm{D}_t = \partial_t + \boldsymbol{u} \cdot \nabla, \quad \Delta = \nabla \cdot \nabla, \tag{3}$$

where ∇ is the gradient with respect to $\boldsymbol{x}$. They are subject to the common no-slip condition $\boldsymbol{u} = \boldsymbol{0}$ holding at the surface. As a well-known characteristic, the stationary Reynolds-averaged turbulent flow can be expressed in terms of the time-averaged motion. In the following we employ the conventional Reynolds decomposition of any (in general, tensorial) flow quantity q into its time-mean component $\overline{q}$, see Fig. 1, here regarded as independent of z, and the (in time and space) stochastically fluctuating contribution q',

$$q(\boldsymbol{x}, t, \ldots) = \overline{q}(x, y, \ldots) + q'(\boldsymbol{x}, t, \ldots), \quad \overline{q} \coloneqq \lim_{\Theta \to \infty} \frac{1}{\Theta} \int_{-\Theta/2}^{\Theta/2} q(\boldsymbol{x}, t + \theta, \ldots)\, \mathrm{d}\theta. \tag{4}$$

Herein the dots indicate any further dependences of q apart from on $\boldsymbol{x}$ and t, e.g. on Re. Reynolds-averaging of Eqs. (2) and (3) then yields the well-established Reynolds equations (in the case $\partial_z \equiv 0$ of planar time-mean flow):

$$\nabla \cdot \overline{\boldsymbol{u}} = 0, \tag{5}$$

$$\overline{\mathrm{D}}_t \overline{\boldsymbol{u}} = -\nabla \overline{p} - \nabla \cdot \overline{\boldsymbol{u}'\boldsymbol{u}'} + \nu \Delta \overline{\boldsymbol{u}}, \quad \overline{\mathrm{D}}_t = \overline{\boldsymbol{u}} \cdot \nabla. \tag{6}$$

It is further presumed in the subsequent analysis that all components of the Reynolds stress tensor $-\overline{\boldsymbol{u}'\boldsymbol{u}'}$ are, in general, of asymptotically comparable magnitude (assumption of locally isotropic turbulence). Most important, we disregard any effects due to free-stream turbulence. That is, the turbulent motion originates from the relatively thin fully

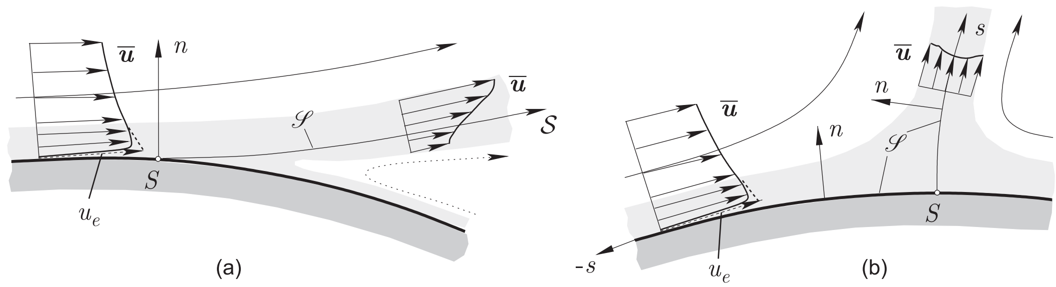

Fig. 1. Time-mean flow near (a) smooth separation (the dotted streamline indicates possible backflow) and (b) separation due to stagnation of the bulk flow, cf. Neish and Smith (1992). The inviscid limit of $\overline{\boldsymbol{u}}$ is shown dashed, and the turbulent shear flow is indicated by a shading.