Abstract

Theoretical and numerical aspects of drag extraction from solutions of the Reynolds-Averaged Navier-Stokes equations are discussed. A new formulation of the theory of far-field / near-field drag balance, due to J. van der Vooren, is presented. This formulation ensures the exact balance of pressure drag plus friction drag (near-field) and viscous drag plus wave drag plus induced drag (far-field). Numerical deviations from the theory, such as spurious drag production and spurious transfer from one form of drag to another, are described, and techniques taking them into account are discussed. The respective accuracy of different formulas (exact, small perturbation, etc.) and techniques (surface or volume integration) is studied. The particular case of flows with supersonic freestream is briefly discussed. Various applications of drag extraction through field analysis are presented: airfoil wave drag control, wing tip devices for induced drag reduction, drag analysis of transonic transport aircraft configurations under cruise conditions, drag analysis of supersonic transport aircraft configurations at transonic cruise and at low speed, drag extraction for unconventional configurations. In discussing the applications, emphasis is put on the specific contribution of the drag extraction technique through field analysis to applied aerodynamics problems and aerodynamic design activities.

Nomenclature

H	stagnation enthalpy
$\Delta H = H - H_\infty$	stagnation enthalpy relative to its freestream value
M_∞	freestream Mach number
R	gas constant
T	temperature
p	static pressure
p_∞	freestream static pressure
$\vec{q}$	velocity vector
Δs	entropy relative to its freestream value
u, v, w	velocity components in x, y, z-direction
u_∞	freestream velocity
x, y, z	orthogonal coordinate system; x is freestream direction
γ	ratio of specific heats
ρ	density
ρ_∞	freestream density
$\vec{\tau}_x = [\tau_{xx}\tau_{xy}\tau_{xz}]^T$	vector of viscous deviatoric stresses
$[\tau] = [\vec{\tau}_x\vec{\tau}_y\vec{\tau}_z]$	matrix of viscous deviatoric stresses

1 Introduction

In the 1970's, computational codes were used in applied aerodynamics to predict pressure distributions, lift and moment coefficients and, for two-dimensional flows, also separation. It would have been deemed unreasonable (for three-dimensional applications at least) to trust the drag value provided by a code, or even to mention it. Computations in two-dimensional inviscid subsonic flow usually predicted positive drag when it should be zero, and now and then unlikely negative values were found.

In the 1980's, with the increasing size of the grids allowed by progress in computer technology, drag became "mentionable" in computational fluid dynamics. J.W. Slooff gave an overview of the subject in 1985, with the significant title *Computational Drag Analysis and Minimization; Mission Impossible?* [1], in which he emphasized the far-field approach to drag extraction, as a promising alternative to the classical and straightforward surface stress integration. The topic was simultaneously addressed by R.C. Lock [2].

A synthesis on the theoretical aspects of the far-field approach by J. van der Vooren and J.W. Slooff appeared in 1990 [3]. During the following decade several developments were carried out and applied in Europe and in America, of which C.P. van Dam published an extensive review in 1999 [4].

Drag prediction based on computational fluid dynamics is related to other topics, *e.g.* turbulence modelling, transition prediction, grid strategy, etc. This lecture is limited to drag extraction itself, *i.e.* how to post-process a given numerical solution to obtain drag with the best numerical accuracy achievable, and in a form that will be most useful to the aircraft designer.

The far-field approach (sometimes called field analysis, or control volume approach), which provides a breakdown of drag into its physical components, viscous drag, wave drag and induced drag, and possibly an additional spurious component, will be considered. It is based on the theory of the far-field / near-field drag balance, which will be presented in a new form due to J. van der Vooren [5]. It will be shown that numerical deviations from the theory, responsible for spurious (non physical) drag, must be taken into account in the formulation itself. This will be illustrated by numerical examples. Various applications will be presented, with the objective of demonstrating the specific contribution of far-field drag extraction to applied aerodynamics problems and aerodynamic design activities.

Drag extraction is only a post-processing task. Yet, the subject cannot be treated without starting from conservation laws and basic thermodynamics, then investigating some particular deviations of the numerics from the physics, and lastly assuming the point of view of the design engineer, faced with the problem of the unexpected drag penalty.

2 Theory of far-field / near-field drag balance

2.1 Introduction

The theory of physical drag breakdown presented in this section is due to J. van der Vooren. It is applicable to steady flows described by the Reynolds-Averaged Navier-Stokes equations, with subsonic freestream state. Although this thory was developed for motorised aircraft configurations, only the case of a non motorised aircraft will be considered here.

2.2 Conservation laws applied to drag formulation

Conservation of mass and of x-momentum (the axes considered are those of the aerodynamic frame of reference, x = freestream flow direction) requires

$$div(\rho\vec{q}) = 0 \tag{1}$$

and

$$div(\rho u\vec{q} + p\vec{i} - \vec{\tau}_x) = 0 \tag{2}$$

Combination of eqs.(1) and (2) gives

$$div[\rho(u - u_\infty)\vec{q} + (p - p_\infty)\vec{i} - \vec{\tau}_x] = 0 \tag{3}$$

Notation $\vec{f}$ will be used for this vector:

$$\vec{f} = -\rho(u - u_\infty)\vec{q} - (p - p_\infty)\vec{i} + \vec{\tau}_x \tag{4}$$

In the flow control volume V (figure 1), $\vec{f}$ has the following property:

$$div\vec{f} = 0 \tag{5}$$