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Automatic Transition Predictions Using Simplified Methods

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Laminar-turbulent transition remains a critical issue in a number of cases, including drag reduction, performance prediction of high-lift systems, improved accuracy in general computational fluid dynamics, and reduction of computation cycles for development of optimization tools. Transition delay remains one of the most promising technologies for reducing air transport energy consumption, through natural or hybrid laminar flow control. The use of linear stability theory, either local or nonlocal, remains rather demanding in terms of knowledge and user interaction. Hence, a demand exists for simplified, robust, and accurate transition prediction tools to be inserted into general flow solvers, of boundary-layer or Reynolds-averaged Navier–Stokes types. The problem can be solved by developing transition criteria or database methods. In this last case, characteristics of an actual flow are derived from known solutions of model flows. ONERA, the French Aerospace Laboratory, has long been involved in the development of such methods, and the present paper aims at providing a comprehensive view of the tools developed in the second category, applicable from low-speed two-dimensional to transonic three-dimensional flows, and even to three-dimensional supersonic flows.

Nomenclature

F = reduced frequency
f = frequency
Hi = incompressible shape factor
P_i = characteristic parameter for the crossflow models
R_k = Reynolds number based on length k
T_w = wall temperature
Ue, We, Te = velocity components and temperature at the boundary-layer edge
U_i = velocity at the location y_i of the inflection point
u, w, T = velocity and temperature components of the boundary-layer profile
V_g, φ_g = modulus and direction of the group velocity
α, β = complex, reduced wave numbers ($\alpha = \alpha^* \delta_1$). Their real parts are the components of the wave vector $\mathbf{k}$.
β^* = crossflow wave number. As β_i is usually forced to zero, β^* represents the real part.
δ_1 = displacement thickness
θ = angle between the local x direction and the external velocity vector
θ_1 = momentum thickness
λ^* = wavelength of the instability $\lambda^* = 2\pi\delta_1/\sqrt{(\alpha_r^2 + \beta_r^2)}$
ν = kinematic viscosity
ρ = density
σ = amplification rate
φ = angle between the wave vector and the local x direction
φ_w = wing sweep angle
ψ = angle between the wave vector and the local external velocity vector
ω_r = reduced pulsation

I. Introduction

AUTOMATIC and robust laminar-turbulent transition prediction tools are still in demand for improving accuracy of flow computation or development of optimization tools. A number of models have been developed at ONERA, and have been combined into a fairly complete prediction tool which may be inserted into boundary layers or Reynolds-averaged Navier–Stokes (RANS) codes. The aim of the present paper is to provide a comprehensive view of these models, including their use as transition prediction tools inside the 3-D boundary-layer code 3C3D. Selected examples will demonstrate the range of applications by providing comparisons to exact results of linear stability (LST). Ways to implement the database method inside a RANS code will also be discussed, although this remains to be accomplished. Because this paper deals with model presentation and validation, examples will compare N-factor curves obtained using the database and exact LST, and will not discuss practical applications involving method calibration, specific data preparation, and statistical analysis of the results. This would grant a separate paper.

The traditional approach for transition prediction is based on the linear stability theory, either local or nonlocal. The addition of the second-order terms curvature and nonparallelism in the nonlocal approach does not significantly improve correlation of computation to experimental results. Therefore, local theory remains widely used for practical applications.

Whereas stability analysis describes how small, preexisting perturbations will grow in the boundary layer through a normal mode response, the e^N method [1,2] correlates an amplitude level with the beginning of turbulence. Here, $N = \log(A/A_o)$, where A/A_o is the amplitude ratio between the current location and a reference, upstream one. The two most common strategies, envelope and $N_{\mathrm{CF}}/N_{\mathrm{TS}}$, will be discussed later.

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