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Amplitude Method of Laminar-Turbulent Transition Prediction in Three-Dimensional Supersonic Boundary Layer at Swept Wing

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Abstract

Amplitude method describing influence of surface roughness and free-stream turbulence level on laminar-turbulent transition caused by cross-flow instability is developed and tested. In contrast to e^N method it is based on computation of amplitudes of steady and non-steady cross-flow instability modes in the boundary layer. Initial amplitudes of these modes were found from solution of receptivity problem to surface roughness and free-stream turbulence respectively. Subsequent evolution of these disturbances is evaluated by means of non-linear PSE-method modified for perturbations with random phases. Point where sum of amplitudes of steady and non-steady modes reaches threshold value is treated as transition location. Method developed was verified using available experimental data obtained in low-speed wind tunnels and applied to transition prediction at the swept wing for supersonic flow velocity.

Keywords: swept wing, receptivity, laminar-turbulent transition

Laminar-turbulent transition at the swept wing is rather sensitive to surface roughness and level of free-stream turbulence [1,2]. These parameters are different in wind-tunnel experiments and in flight conditions, so transition location is not reproduced in wind-tunnel tests. Because of remarkable contribution of friction drag into total drag of airplane, prediction of transition line at the wing and empennage is necessary for correct finding of aerodynamic characteristics of supersonic passenger aircraft. Such airplanes generally have triangular of swept wings with subsonic leading edges and relatively large sweep angle. Laminar-turbulent transition at these wings is cased by cross-flow instability. In low-turbulence environments (flight conditions) transition is triggered by steady modes generated by surface roughness, but in industrial wing tunnels it is caused by travelling or non-steady modes initiated by free-stream turbulence. Correct transition prediction method should take into account the amplitude and nature of ambient disturbances. Nevertheless, modern e^N method of transition prediction is based on analysis of amplification of disturbances in the boundary layer and ignore all other physics. Influence of surface roughness and flow turbulence are generally accounted for by means of empirical correlations for dependence of N-factor from these parameters [3,4]. However, such correlations are suitable for narrow range of parameters.

Alternative amplitude method of cross-flow dominated transition prediction based on computation of amplitudes of steady and traveling cross-flow instability modes is developed here. Initial amplitudes of disturbances in the boundary layer are found by means of decomposition of free-stream turbulence and surface roughness into a set of periodical waves and consideration of generation of Eigen modes in the boundary layer by these elementary waves via non-localized receptivity mechanism [5]. Subsequent evolution of steady and non-steady modes with continuous spectra and random phases is computed by simplified non-linear PSE-method. Transition location is determined as a place where the sum of amplitudes of steady and non-steady modes reaches a threshold value 0.34. This transition criterion was recently introduced from analysis of experimental data for wide range of surface roughness and turbulence level in [6].

The amplitude method developed reproduces satisfactorily the dependence of transition location on the Reynolds number, the surface roughness, and free-stream turbulence level observed in experiments [1,2] (see Figure 1,a). Moreover, it gives the evolution of almost all measurable characteristics of the base flow and perturbations in the transition region. In particular, it describes saturation of the growth of steady and traveling modes and the deformation of the velocity profiles in the boundary layer initiated by these modes (see Figure 1, b, c).

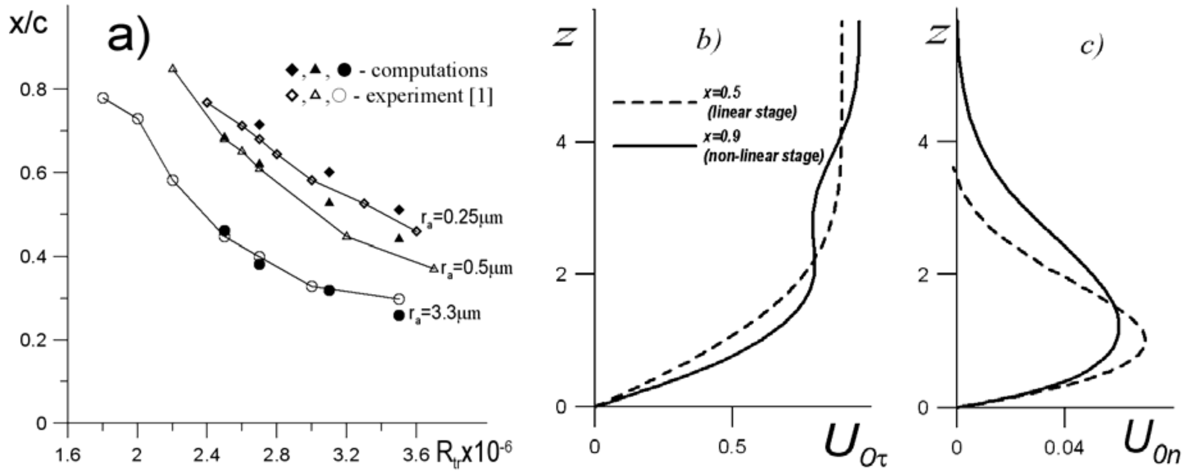

Fig 1. . Transition location at the swept wing as function of Reynolds number: comparison of computations with experiment [1] (a), Deformation of profiles of tangential (b) and cross-flow (c) velocity in the boundary layer in the transitional region (computations).

Amplitude method developed was applied to evaluation of dependence of transition location on the schematized swept wing with sweep angle 60^0 for M=2 from surface roughness and turbulence level. Computations were performed for typical size of aircraft (chord 5m) and model with chord 0.5m and the same Reynolds number 30 millions. It was found that transition location at the model is sensitive to surface roughness amplitude 0.2 microns and turbulence level 0.2-0.3%. Transition at natural size is sensitive to large roughness of 3-5 microns.

Amplitude method of transition prediction developed is rather simple and does not require large amount of computations. It can be used in future for operative prediction of transition location instead of e^N method.

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