INFINITE SWEPT-WING REYNOLDS-AVERAGED NAVIER-STOKES COMPUTATIONS WITH FULL E^N TRANSITION CRITERION

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Abstract

A full e^n transition prediction method is coupled to the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) solver to predict the transition point automatically during the simulation of the flow around the infinite swept wings. The three-dimensional linear stability equations are solved using the Cebeci-Stewartson eigenvalue formulation. The locations of the calculated transition points are validated by the experimental results. With the reliable transition information, the accuracy of the infinite swept wing's aerodynamic performance calculated by the RANS solver has been improved.

1 Introduction

It is well known that if the transition information of the boundary layer flow is not included, the wing's aerodynamic characteristics calculated by the RANS solver will not be accurate enough. The characteristics between the laminar flow and turbulent flow are very different, for example, the wall friction caused by turbulence flow is several times higher than that caused by laminar flow. Hence, without taking into account the boundary layer flow's transition point, or miscalculating the transition point, the calculated wing's aerodynamic characteristics, especially the drag characteristic will be a far cry from the experimental value. At the same time, ignoring the boundary layer flow's transition information, the calculation accuracy of boundary layer heat conductivity will reduce at least 25% [1].

On the other hand, the method which can accurately predict the transition location is one of the key technologies for designing the natural laminar flow wing. In order to improve the performance of the aircraft and to reduce air pollution during the cruise, the cruise drag needs to be reduced. In general, for a typical swept-winged transport aircraft at cruise, the frictional drag accounts for about 35% of the total drag [2], so among the various drag reduction technologies, the laminar flows drag reduction is one of the most promising technologies. However, the design of natural laminar flow wing on which a wide range of laminar flow can be maintained must be based on the reliable transition prediction method.

Because of the complexity of the transition from the laminar flow to turbulence flow, yet we cannot make a complete explanation of its mechanism. However, after half a century's theoretical and experimental research, there has been quite in-depth understanding of the transition mechanism and a lot of methods for predicting the boundary layer transition point have been developed. Among those methods, the e^n method proposed by Smith, Gamberoni [3] and Van Ingen [4], which based on the linear stability theory, has been widely used in industry. In view of the e^n method has been successfully applied in two-dimensional boundary layer transition determination, Malik [5], Mack[6], Arnal[7], Cebeci[8] and other investigators introduced this method into determining the three-dimensional boundary layer's transition. Especially during the past decade, the National Aeronautics and Space Administration (NASA), the German Aerospace Center (DLR), the French Aerospace Center (ONERA) and the other research institutes have been carrying out a method of coupling the simplified e^n method to the three-dimensional Reynolds-averaged Navier-Stokes solver in order to increase the accuracy of solving aerodynamic performance for the wing, the high lift devices and the aircraft. The simplified e^n method owing to its rapid response speed has been widely used, but as the computer performance significantly improved, the use of a full e^n approach is also feasible. In this paper, we couple the full e^n method to the three-dimensional Reynolds-averaged Navier-Stokes solver to increase the solver's accuracy.

The computational methods for predicting the transition point based on the Cebeci-Stewartson eigenvalue formulation [8] is described in section 2. Section 3 answers the question: how to couple the RANS solver with the transition prediction method? In section 4, we validate the reliability of the transition prediction method described in this paper by comparing the calculated results with the experimental results, and the result of the comparison approves the reliability of above method.

2 Computational Method

As mentioned above, it is an iterative process to determine the transition point using the e^n method during solving the three dimensional Reynolds-averaged Navier-Stokes (RANS) equations. Each iterative process contains three programs which will be described in detail in the following sections.

2.1 Three-Dimensional RANS Solver

The three-dimensional, unsteady, compressible RANS equations in our solver are solved by means of a finite volume approach using a LU-SGS time-stepping method with multi-grid acceleration, and the SA turbulence model is applied. In boundary-layer theory, the pressure gradient is nearly zero along the wall normal direction inside the boundary-layer region. For this reason, the wall pressure distribution from RANS solutions is used as the outer boundary condition for the boundary-layer solution.

2.2 Three-Dimensional Laminar Boundary Layer Solver

As we all know that the prediction of transition in the flows around wings with the e^n prediction transition method requires the specification of velocity and temperature profiles of the laminar boundary layers. Generally there are two ways to obtain the velocity and temperature profiles, either the solutions of the RANS or the boundary- layer equations. In our paper, we use the latter method to get the velocity and temperature profiles because the former method need a lot of grid point in the region of boundary layer to obtain accurate viscous-layer results which will cost huge compute time. This was confirmed by Stock, H. W. [9]. In order to solve the boundary-layer on arbitrary wings, we utilize a non-orthogonal coordinate system for defining the wings. Keller's box method is used to discrete the three-dimensional laminar boundary-layer equations, and then, using the Newton method to linearize above nonlinear equations, finally, the Block-Elimination method is used to solve the linear system.

2.3 Transition Prediction Solver

Unlike the simplified e^n method, such as the e^n – database method or the envelope method, which do not need to solve the linear stability equation for detecting the transition location, the present full method uses the Cebeci-Stewartson eigenvalue formulation which is based on the spatial amplification to solve the Orr-Sommerfeld equation for three-dimensional flows.

In the solution of three-dimensional linear stability equation, the eigenvalue formulation requires a relationship between the two wave numbers α and β . In the Cebeci-Stewartson eigenvalue formulation the relationship is computed by making use of concepts based on group velocity using the saddle-point discussed by Cebeci and Stewartson[8] and Nayfeh[10]. According to the saddle point method the formulation $(\partial\alpha/\partial\beta)_{\omega,R}$ is real and related by the disturbance angle ϕ through

$$\left(\frac{\partial\alpha}{\partial\beta}\right)_{\omega,R} = -\tan\phi \quad (1)$$

The Eq. (1) provides a relationship between the two wave numbers as needed in the eigenvalue problem.

The procedure through using the full e^n method to determine the three dimensional boundary layer flows' transition points contains two steps. The first step is to calculate the absolute neutral curve which was named as "zarf" by Cebeci. The zarf passes through the critical points in α,β,ω,R space at which $R = R_{cr}$ and is of significant importance in transition point prediction for three dimensional flows. The second step is to calculate the amplification rate for different dimensional frequencies beginning on the lower branch of the zarf. The amplification rate Γ is:

$$\Gamma = -\alpha_i + \beta_i\left(\frac{\partial\alpha}{\partial\beta}\right)_{\omega,R} \quad (2)$$

The onset of transition may be evaluated by solving the integral

$$N = \max_f\left[\int_{x_0}^{x} \max_\phi\left(\Gamma(\phi)\right)dx\right] \quad (3)$$

Where f is the dimensional frequency $\omega^*/2\pi$, ω^* is the dimensional radian frequency, x_0 corresponds to the x-location where the amplification rate is zero on the zarf. Once the amplification factor N is greater than a limiting factor N_{limit}, then the transition happens.

3 Calculation Procedures

A Reynolds-averaged Navier-Stokes code, a laminar boundary code and a full e^n prediction transition method are coupled (see Fig. 1). First, the flow simulation begins with full turbulence model by the RANS solver. As soon as the steady flow is established, the surface pressure coefficient c_p of the wing is calculated by the RANS solver for determining the outer boundary condition of the laminar boundary layer. Second, after the laminar boundary layer's outer boundary condition is calculated, the three-dimensional laminar boundary layer equations can be solved. Then, we use the linear stability code to analyze the laminar boundary's velocity and temperature profiles applied by the boundary layer solver, and find out the transition point with the full e^n method. If there does not find transition point by using the full e^n method, setting the laminar separation point as the transition point approximately. Finally, we returned the transition information to the solution of RANS equations. Repeat the above process, the flow transition point was detected automatically during the ongoing RANS computation.

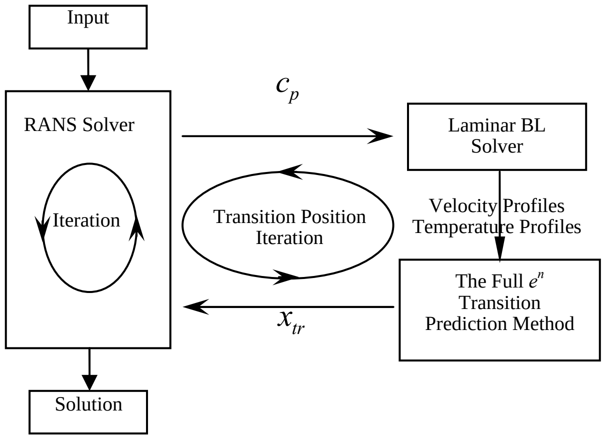


Fig.1 Sketch of the coupling the RANS solver with the transition prediction method

4 Results

We studied two infinite wing configurations by comparing their calculated transition locations and the measured transition locations to validate our transition prediction method. The two infinite wing sections normal to the leading edge are NACA 642A015 and NLF(2)-0415 airfoils respectively.

4.1 Infinite Swept Wing with NACA 64_2 A015 Profile

The infinite swept-wing with the NACA 64_2 A015 profile was tested in the NASA Ames 12-Foot Low Turbulence Pressure Tunnel [11]. The tested Reynolds numbers range from 3.8×10^6 to 29.0×10^6 , and sweep angles are 10, 20, 30 deg. The transition measurements were executed on the upper surface of the wing. According to the reference [12], when the swept angle less than 30^o and angle of attack great than 0^o that is the Tollmien-Schlichting(TS) waves which cause the flow transiting from laminar to turbulence. Here, we use our method to detect the transition locations at the state above.

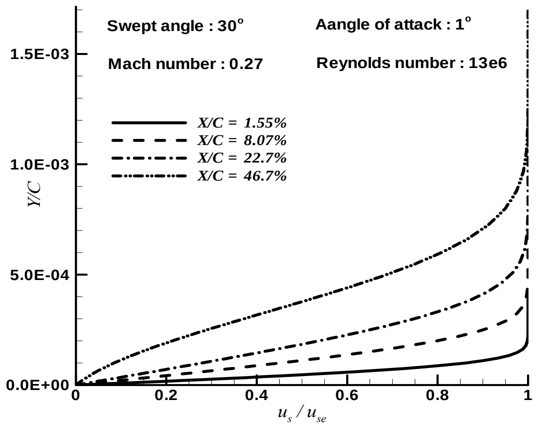


Fig. 2. Computed streamwise velocity profiles u_s/u_{se} for M_∞=0.27 at various X/C stations.

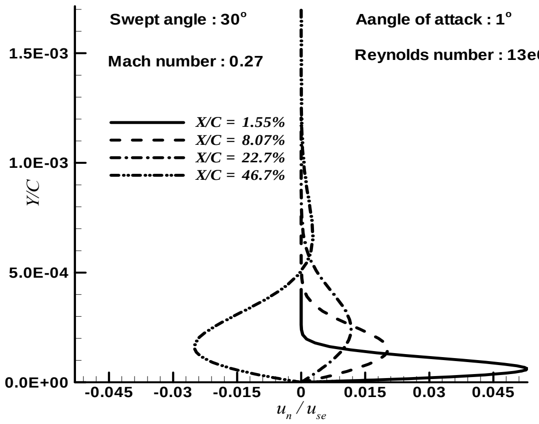


Fig. 3. Computed streamwise velocity profiles u_n/u_{se} for M_∞=0.27 at various X/C stations.

First, we detect the transition point on the upper surface of the swept wing with swept angle $\lambda=30^o$ at a state to illustrate the transition prediction procedure through using the full e^n transition method, see Fig.2 to Fig. 6. The flow conditions are Mach number M_∞=0.27, angle of attack $AOA=1^o$ and Reynolds number R= 13× 10^6. Fig. 2, Fig.3, Fig. 4 show the streamwise velocity, crossflow velocity and temperature profiles respectively which calculated by solving the three dimensional boundary layer equations whose out-edge boundary conditions are determined by the wall pressure coefficient c_p which is calculated by the RANS solver. Fig. 5 shows the variation of dimensionless radian frequency ω on zarf which solved by the linear stability equations. The laminar boundary layer's velocity profiles, temperature profiles and their first, second derivative are the input of the three dimensional compressible linear stability solver. Once obtaining the radian frequency ω on the zarf, according to the e^n method, we track a series of disturbances with fixed dimensional frequency each to trace their development along the streamwise. In order to make sure the transition procedure automatically, we chose fifteen frequencies that evenly distribute on the zarf. Fig.6 shows the variation of the amplification factor with respect to the dimensionless radian frequency ω which is selected in the Fig. 5.

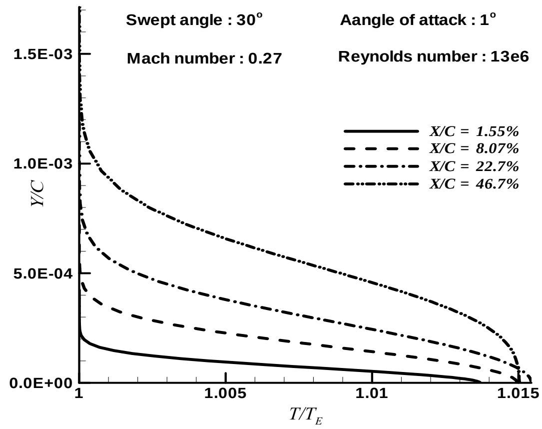


Fig.4. Computed temperature profiles T/T_e for M_∞=0.27 at various X/C stations.

As we all know that the e^n method is a semi-empirical method and the stability limit N_{limit} used for predicting the transition point is an unknown priori, and it must be determined through the experiment. At this flow condition, the measured transition point is at about 40% of the chord where the calculated N factor is about 10.5 through the full e^n method.

Fig. 7, Fig. 8 and Fig. 9 show the measured and computed transition locations with different limiting N_{limit} factors near the 10.5 (9, 10, 10.5, 11) on the upper surface of the infinite swept wing with the NACA 64_2 A015 profile for three swept angles (10^o, 20^o, 30^o) and two angles of attack (0^o, 1^o). As can be seen from the above figures, when the limiting N_{limit} factor is taken as 10.5, the calculated transition locations agree well with the measured transition locations.

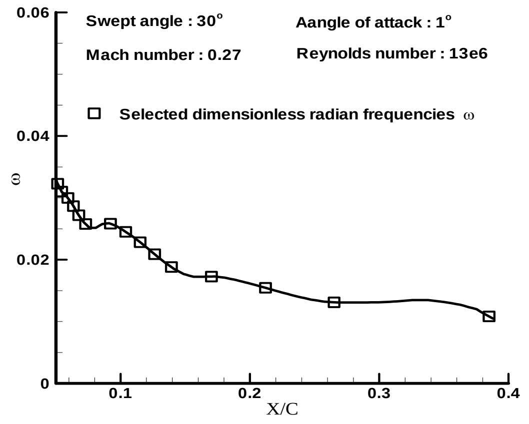


Fig. 5. Variation of ω on zarf for M_∞=0.27 on the upper surface of the infinite swept wing model.

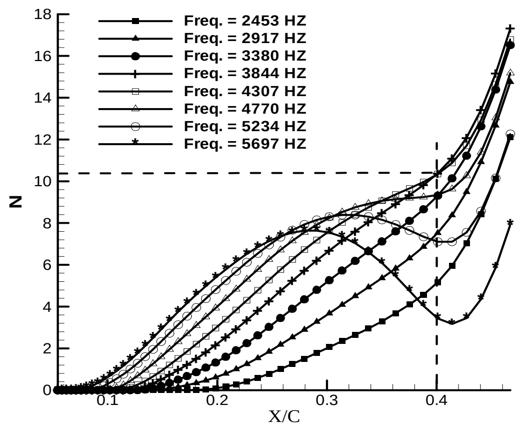
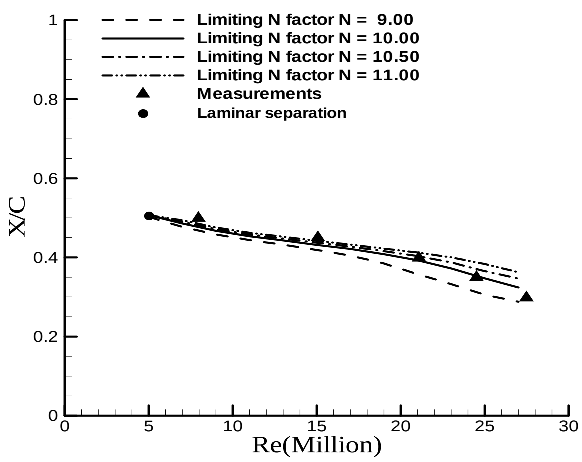
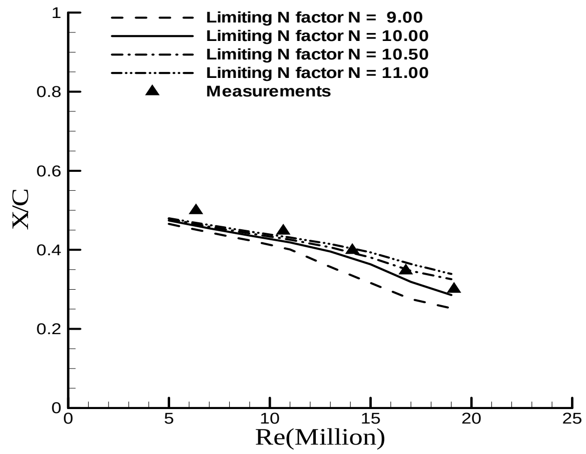


Fig. 6. Variation of the amplification factors for the frequencies of Fig.5.

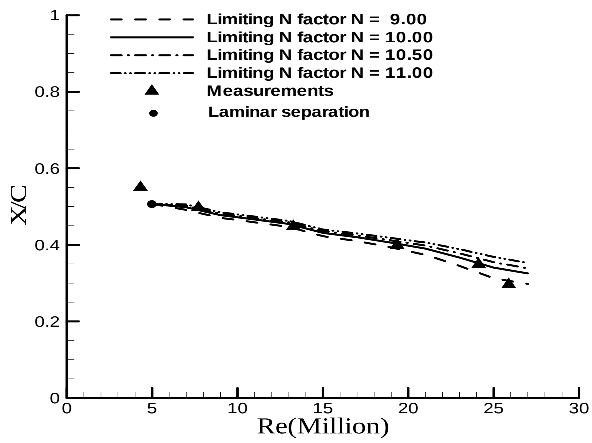


(a) Angle of attack is 0°

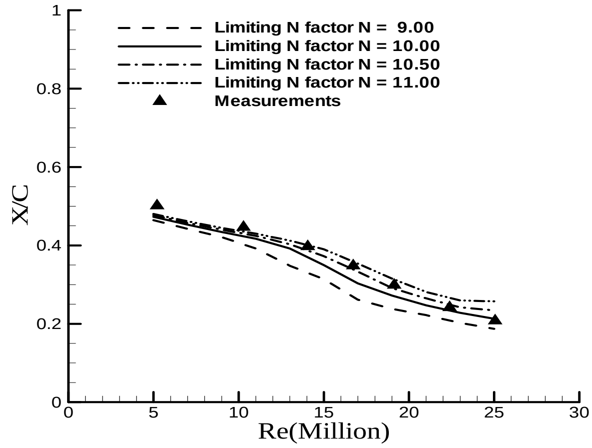


(b) angle of attack is 1°

Fig. 7. Measured and computed transition locations on the upper surface of the infinite swept-wing with λ=10°.



(a) Angle of attack is 0°



(b) Angle of attack is 1°

Fig. 8. Measured and computed transition locations on the upper surface of the infinite swept-wing with λ=20°

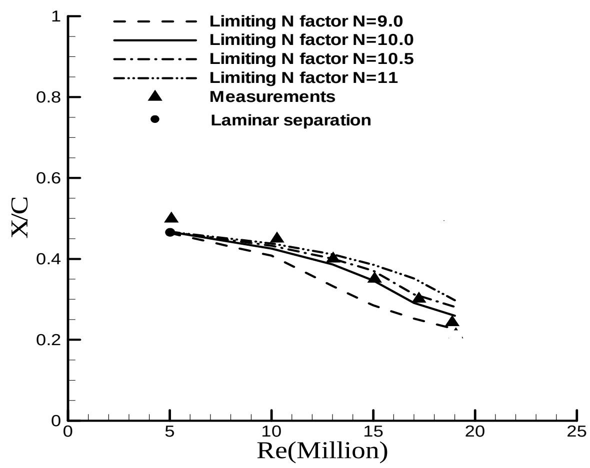


Fig. 9. Measured and computed transition locations on the upper surface of the infinite swept-wing with $\lambda=30^{o}$ at angle of attack 1^{o}.

4.2 Infinite Swept Wing with NLF(2)-0415 Profile

The infinite swept-wing with the NLF(2)-0415 profile was tested in the Arizona State University unsteady low-speed wind tunnel at a sweep angle of 45 degree, and an angle of attack of -4 degree[13]. At this state, the transition of the flow from laminar to turbulence is caused by the crossflow (CF) waves.

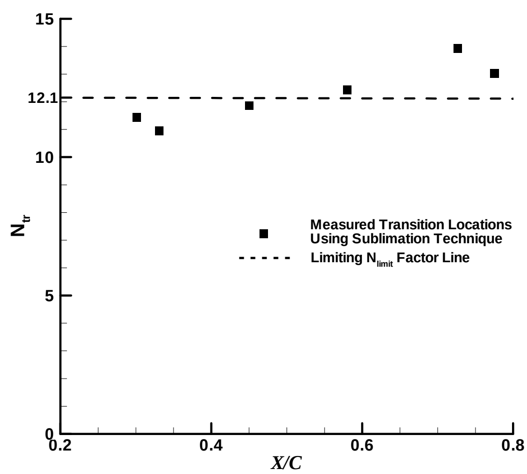


Fig. 10. N_{tr}-X/C diagram on the surface of the infinite swept wing model with the NLF(2)-0415 profile.

Fig. 10 shows another way to determine the limiting N_{limit} factor. In this way, we calculate the N_{tr} factors correspond to the transition locations measured through experiment techniques, and we can get a diagram of N_{tr}-X/C, see Fig. 10. Then, the limiting N_{limit} factor can be determined as 12.1 from Fig. 10. Fig. 11 shows the comparison between the computed transition position with the limiting N_{limit} factor as 12.1 and the measured transition position on the upper surface of the infinite swept wing, and we find the calculated values are basically distributed in the experimental range.

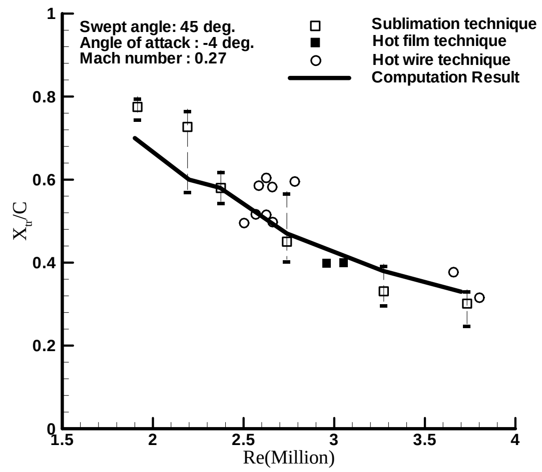


Fig. 11. The comparison between the computed transition position with the limiting N_{limit} factor as 12.1 and the measured transition position on the upper surface of the infinite swept wing model with the NLF(2)-0415 profile.

5 Conclusions

A full e^n transition method which needs to solve the linear stability equations is coupled to the three-dimensional RANS solver in order to automatically detect the transition locations during the calculation of the wing's aerodynamic. The reliability of this method is validated by comparison with experimental results. The transition locations are predicted for two configurations whose transitions are caused by the TS waves and the CF waves respectively. The limiting N_{limit} factor is different for transition dominated by TS wave or CF wave, and it is determined by the experimental results. With the help of the experimental results, the computed transition locations are shown to agree well with the experimental results.

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References

[1] Reed H L, Saric W S. CFD Validation Lssues for Boundary-Layer Stability and Transition. AIAA Paper No.2003-3441.

[2] John E G. Laminar Flow Control – Back to the Future? AIAA Paper No. 2008-3738.

[3] Smith A M O, Gamberoni N. Transition, Pressure Gradient and Stability Theory. Douglas Aircraft Co., Rept. ES 26388, Long Beach, CA, 1956.

[4] Van Ingen J L. A Suggested Semi-Empirical Method for the Calculation of the Boundary Layer Transition Region. Dept. of Aerospace Engineering, Rept. VTH-74, Univ. of Delft, Delft, the Netherlands, 1956.

[5] Malik M R. COSAL – A Black Box Compressible Stability Analysis Code for Transition Prediction in Three-Dimensional Boundary Layers. NASA CR - 165925, 1982.

[6] Mack L M. Stability of Three-Dimensional Boundary Layers on Swept Wings at Transonic Speeds. IUTAM Symposium, Transsonicum III, Göttingen, May 1988.

[7] Arnal D, Casalis G and Juillen J C. Experimental and Theoretical Analysis of Natural Transition on Infinite Swept Wing. IUTAM Symposium, Toulouse, France, 1989, *Laminar-Turbulent Transition* (eds. D. Arnal, R. Michnel) Springer-Verlag, pp 311-326, 1989.

[8] Cebeci T, Stewartson K. On Stability and Transition in Three-Dimensional Flows. *AIAA J.*, Vol. 18, No. 4, pp 398-405, 1980.

[9] Stock H W, Haase Werner.Feasibility Study of e^N Transition Prediction in Navier–Stokes Methods for Airfoils. *AIAA J.*, Vol. 37, No. 10, pp 1187-1196, October 1999.

[10] Nayfeh A H, Stability of Three-dimensional Boundary Layers. *AIAA J.*, Vol. 18, pp 406-416, 1980.

[11] Boltz F W, Kenyon G C and Allen C Q. Effects of Sweep Angle on the Boundary-Layer Stability Characteristics of an Untapered Wing at Low Speeds. NASA TN-D-338, Aug. 1960

[12] Stock H W, Infinite Swept-Wing Navier-Stokes Computations with e^N Transition Prediction. *AIAA J.*, Vol. 43, No. 6, pp 1221-1229, 2004.

[13] Dagenhart J R, “Cross-Flow Stability and Transition Experiments in a Swept-Wing Flow. NASA TM-108650, March 1992.

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