A computational study on robust prediction of transition point over NACA0012 aerofoil surfaces from laminar to turbulent flows

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Abstract Flow transition from laminar to turbulent is prerequisite to decide whereabouts to apply surface flow control techniques. This appears missing in a number of works in which the control effects were merely investigated without getting insight into alteration of transition position. The aim of this study is to capture the correct position of transition over NACA0012 aerofoil at different angles of attack. Firstly, an implicit, time marching, high resolution total variation diminishing (TVD) scheme was developed to solve the governing Navier–Stokes equations for compressible fluid flows around aerofoil sections to obtain velocity profiles around the aerofoil surfaces. Secondly, the linear instability solver based on the Orr–Sommerfeld equations and the e^N methods were developed to calculate the onset of transition over the aerofoil surfaces. For the low subsonic Mach number of 0.16, the accuracy of the compressible solutions was assessed by some available experimental results of low speed incompressible flows. In all cases, transition positions were accurately predicted which shows applicability and superiority of the present work to be extended for higher Mach number compressible flows. Here, transition prediction methodology is described and the results of this analysis without active flow control or separation are presented. [doi:10.1063/2.1304204]

Keywords transition prediction, hydrodynamic stability, laminar flow control, TVD solver, aerofoil

Early in the 1970s, the OPEC oil embargo caused many aircraft manufacturer companies to focus on improving aerodynamic efficiencies.[1] For many years, advancement and development of new commercial aircrafts for more profitability has been one of the aims of manufacturer companies. Increasing efficiency of an aircraft may lead to substantial saving in operational costs. For example, reducing drag of an aircraft for only one percent may lead to a great saving in annual fuel costs for an airline company.

The purpose of this study is to examine several examples of laminar flow control especially over the aerofoil surfaces with a desired flow control technique. For achieving this, it is required to solve flow field equations and determine transition location accurately. In this paper, an implicit, time marching, high resolution total variation diminishing (TVD) scheme is considered. Sedaghat[2] used it to solve the governing two-dimensional Navier–Stokes (NS) equations for fluid flows over the aerofoil. To determine the transition location, the e^N method is employed. This method is based on linear stability theory, and use the eigenvalues and eigen functions of Orr–Sommerfeld equation to determine the amplification rates of disturbance waves. To solve the Orr–Sommerfeld equation, velocity profiles and their derivatives within the boundary layer at all sections in the stream wise direction are required. This is obtained by solving the NS equations around aerofoil surfaces assuming laminar flow everywhere.

In all cases reported in this paper (flows around aerofoils at all angles-of-attack and Reynolds numbers), flow separation occurred after transition point. This means that the linear stability analysis is commenced by solving the Orr–Sommerfeld equation before transition location with velocity profiles not separated. With these profiles, the linear stability theory is employed to determine transition point.

It should be noted that if flow separation occurs before transition point, then onset of transition may be influenced by separated flow behavior, which is not considered in this paper. For modeling of separated-flow transition, the common approach is based on superposition of the effects of two different types of instability, Kelvin–Helmholtz instability and Tollmien–Schlichting instability. The predominance of instability determines the modes of separated-flow transition. The proposed classification of the separated-flow transition modes takes into account the location of separation relative to onset of transition.

For relatively large Reynolds numbers and mild adverse pressure gradients, the start of transition is induced by the Tollmien–Schlichting instability mechanism. For this kind of instability, any initial disturbance is adverted by the flow as it is amplified and interacts with the inflectional instability.[3]

Recently, Goodarzi et al.[4] have studied the concept of active flow control using a blowing jet over NACA0015 airfoil's upper surface at $Re = 4.55 \times 10^5$ in different high angles of attack using FLUENT. Their simulation results show that the blowing increases the amount of lift and reduces drag. Also at high angles of

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attack, the blowing delays separation and improves the performance of the airfoil. Goodarzi et al.[5] also studied flow control over NACA0012 airfoil in different angles of attacks with three different suction ratios of 0.173, 0.337, 0.5 using FLUENT. Their results show that the flow separation is delayed and the ratio of lift to drag is increased at the slot location of 10% of the chord length and the suction ratio of 0.5. The flow remains attached at the upper surface of the airfoil up to the high angle of attack of 21°. In both previous works,[4,5] the incompressible flow was assumed and no transition criterion was used.

This paper focuses on the onset of transition since transition precedes separation. For this task, the behavior of Tollmien–Schlichting waves is analyzed. Then, the stability analysis is conducted by solving the Orr–Sommerfeld equation. Next, the location of transition point is determined with the e^N method. Finally, the flow field is solved in both laminar and turbulent regimes independently, i.e., from stagnation point near the aerofoil leading edge to transition point as laminar regime and from transition point to aerofoil trailing edge and wake region as turbulent regime.

A class of implicit, second order accurate, high resolution, TVD scheme is adopted here for computation of two dimensional NS equations of compressible flows. The method is based on upwind and symmetric TVD schemes reported by Yee[6] and further modified by Sedaghat[2] for computation of viscous compressible flows. A hyperbolic grid generator with clustering mesh points in the boundary layer is used to generate C-type orthogonal meshes around aerofoil sections.

The NS equations in non-dimensional form are solved in a uniformly spaced rectangular computational domain obtained from any physical mesh in 2D geometries. Free stream Mach number, Reynolds number, and angle of attack are specified as input parameters to the TVD code. The velocity profiles in the boundary layer are accurately obtained when the solution converged. The cases studied here are fully attached flows and no separation occurs over the aerofoil section.

In this study, the turbulent viscosity coefficient μ_t is determined using the algebraic eddy-viscosity model proposed by Baldwin and Lomax.[7] The effect of mass transfer at the wall is modelled in Baldwin–Lomax turbulence model[7] using modification to Van Driest factor (A^+). Changing in A^+ is firstly proposed by Cebeci[8] and then modified by Chokani and Squire,[9] and A^+ is presented as

$$A^+ = 26\left[e^{11.8v_w^+} - \frac{p^+}{v_w^+}(e^{11.8v_w^+} - 1)\right]^{-\frac{1}{2}}, \tag{1}$$

in which v_w^+ is suction speed at the wall and

$$p^+ = \frac{-\mu_w}{Re_\infty \rho_w^2 u_\tau^3}\left(\frac{dp}{d\xi}\right)_w, v_w^+ = \frac{v_w}{u_\tau}, u_\tau = \sqrt{\frac{\tau_w}{\rho_w}}, \tag{2}$$

where μ_w and ρ_w are molecular viscosity and density at the wall, Re_∞ is free stream Reynolds number, $(dp/d\xi)_w$ is pressure gradient in the stream wise direction at the wall, u_τ is friction velocity, and τ_w is shear stress at the wall.

An efficient finite difference method is used for solving the eigenvalues corresponding to the Orr–Sommerfeld equation. The numerical algorithm can be found in Ref. 10. The method is highly dependent on an initial estimation for required parameters. In case of improper guess, the method may diverge. To overcome this problem, some artifices are adopted including Newton iteration method for solving non-linear equations and a relation specified to compute initial values from pervious grid point values.[10–12]

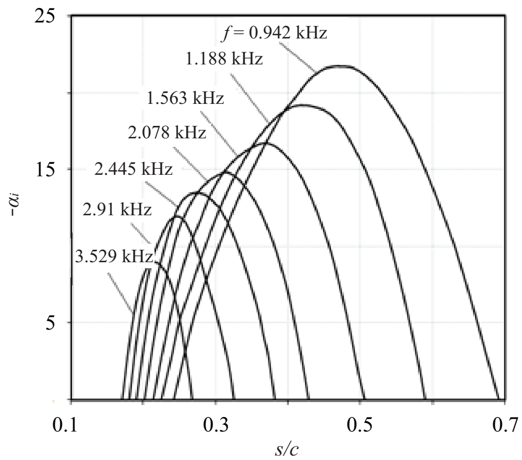
For transition prediction with the e^N method, $N = 9$ is selected for the flow around 2D aerofoil sections in wind tunnels with turbulent intensity levels less than 0.1% based on the comparison of the results and experimental data obtained by Gregory and O'Reilly.[13] Some researchers, like Cebeci et al.,[10] Stock and Haas,[14] and Crouch et al.,[15] also suggested this value for the flow around 2D aerofoils in wind tunnels with $Tu < 0.1\%$.

The computed transition positions using the e^N method are compared with experimental data obtained by Gregory and O'Reilly[13] in Table 1 for several angles of attack. For small angles of attack, there is an excellent agreement with experimental data. However, for higher angles of attack (AOA) (> 5°) when separation may also occurs, a small discrepancy is observed between the e^N method and experimental data. For these cases, transition onset occurs mainly near the aerofoil leading edge till 10% chord distance from the aerofoil leading edge. At this area the high surface curvature of the aerofoil has a very important effect on the flow which forces the flow to twist on the surface rapidly. This and separation effects are the main cause of those discrepancies between the e^N method and the experimental data.

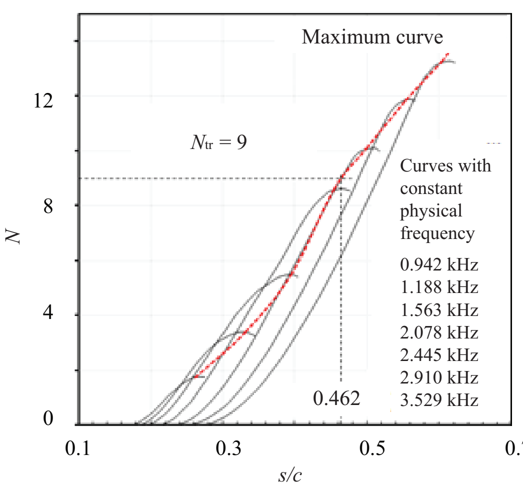
Table 1. Comparison of the e^N method results with experimental data[13] for transition locations over upper and lower surfaces of NACA0012 aerofoil.

AOA/(°)	x_{tr} (upper surface)		x_{tr} (lower surface)	
	e^N method	Ref. 13	e^N method	Ref. 13
0	0.436	0.45	0.436	0.45
1	0.362	0.37	0.550	0.56
2	0.274	0.29	0.608	0.62
3	0.181	0.19	0.653	0.66
4	0.126	0.12	0.701	0.70
5	0.091	0.076	0.734	0.74
6	0.064	0.051	0.802	0.82
7	0.049	0.036	0.877	0.89
8	0.024	0.018	0.957	0.98
> 8	Leading edges		Trailing edges	

Using the aforementioned flow solutions for velocity profiles around NACA0012, the Orr–Sommerfeld equation is solved according to Ref. 12. Values of $-\alpha_i$ (amplification rates) are shown in Fig. 1(a) at seven constant frequency values varied from 0.942 kHz to 3.529 kHz. Figure 1(b) shows the N-values (amplification factors) for the same frequencies. The transition point is also determined with the e^N method as shown in Fig. 1(b). The maximum of the amplification rates (dashed line in Fig. 1(b)) indicates that for $N = 9$, the onset of transition occurs at the section $s_{\rm tr} = 0.462c$, or at $x_{\rm tr} = 0.436c$.



(a) Spatial amplification rate ($-\alpha_i$) curves



(b) Transition prediction using the e^N method

Fig. 1. Flow stability analysis for the flow around NACA0012 aerofoil.

A question may arise on why the e^N method has been so widely used based on a linear theory for predicting transition whilst transition to turbulence itself is a highly non-linear phenomenon. This is because there are inherent difficulties for predicting transition. On the other hand, the method appears to contain enough physical information to allow prediction of the distance to transition with only a short semi-empirical extension. For 2D incompressible flows at low turbulence levels, the linear part of the amplification process seems to cover a large percentage (75%–85%) of the distance between first instability and transition which is estimated by Obremski, Morkovin, and Landahl (see Ref. 16). Also, the value of N which is prescribed for transition, is determined from experimental observations and hence the method still has a good correlation with experimental data.

Flow transition from laminar to turbulent was investigated for NACA0012 aerofoil at different angles of attack. The aim is to accurately predict transition position as a prerequisite to decide whereabouts to apply surface suction or blowing for optimum and better flow control. This paper addresses the drawbacks of a number of works conducted to assess active suction or blowing control without making enough attention to the alteration of transition position. In this study, an implicit, time marching, high resolution TVD scheme was used to simulate flow field around the aerofoil surfaces by solving the governing NS fluid flow equations. The linear stability theory with e^N method was employed to determine the onset of transition in separate routines. Critical Reynolds number and transition positions for a typical NACA0012 aerofoil were determined accurately in well agreement with some available experimental data. Only attached flows are described here and the work for separated and controlled flows will be reported in separate continuing articles.

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