IMPROVEMENT OF TRANSONIC AEROFOIL AERODYNAMIC PERFORMANCE WITH TRAILING EDGE MODIFICATION USING WEDGE CONFIGURATION

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Abstract

The improvement of transonic aerofoil aerodynamic performance by a way of the aerofoil trailing edge modification is presented. The modification of the aerofoil geometry is performed by adding a wedge configuration on the end of trailing-edge lower surface of the aerofoil. This is a practical way that may be proposed to improve an aircraft performance by placing the optimum wedge configuration on the wing trailing edge.

Performing computational calculation based on Reynolds Averaged Navier-Stokes solution, the results of the modification increase lift, reduce shockwave strength, adverse pressure gradient and wave drag. There is also additional base drag due to the wedge surface, but the amount is relatively less that the decreasing wave drag.

In this research, the RAE 2822 aerofoil is used for a case study and various size of wedge configurations attached at the lower surface of the aerofoil trailing edge are investigated to find the optimum wedge configuration.

1. Introduction

The improvement of transonic aerofoil aerodynamic performance is currently attracting much research since the modern transport aircraft is required to have a longer range and endurance. Increasing the aerofoil aerodynamic performance can also reduce the amount of fuel used for the aircraft to cover a certain range flight. Also, improvements in aerofoil aerodynamic performance for fighter aircraft are required for a better maneuverability. The improvement of aerodynamic performance can be obtained by increasing the aerodynamic efficiency in terms of Mach number times lift over drag.

For the modern transport aircraft where the cruise speed is above the critical speed, the aerodynamic performance is strongly influenced by the presence of regions of both subsonic and supersonic flows existing locally on the upper surface of the aerofoil. A large energy loss occurs when the supersonic flow on the upper surface is terminated by a shock wave and so the drag is increased. In addition, the shock wave produces an adverse pressure gradient on the aerofoil surface that may cause separation of the boundary layer with large drag rise, severe aerofoil buffeting, and stability and control problems.

In order to overcome the above problem, it is required techniques to delay the drag rise onset and to reduce the increased adverse pressure gradient by modifying the aerofoil geometry. A practical aerofoil geometry modification may be accomplished by modifying a part of the trailing edge aerofoil in order to have a given thickness. The first technique is proposed by Holder [1] for the following purposes:

- To increase the thickness-chord ratio without changing the surface slope, and hence to delay the onset of drag rise and separation effects.
- To enable camber to be added without changing the upper surface curvature, and hence provide lift with smaller upper surface super-velocities.

Further advantages of the modified aerofoil using the thick trailing edge are ease of manufacture and increase structural stiffness. The modification of the trailing edge can be performed as follows

- By removing the rear portion of an aerofoil
- By adding a wedge or curvature on the lower surface near the aerofoil trailing edge.

Although both the above modifications are simple to apply to the aircraft wing, the second method is more interesting in several respects. First the added lower surface wedge is like a natural, high speed version of the Zaparka [2], or low-speed version of the Gurney flap; second in wind tunnel testing, the addition wedge is more easily fitted than in the first method. The trailing edge modification using the wedge on the lower surface provides a divergent trailing edge angle and increases aft camber near the trailing edge.

This paper explains the investigation the effects of aerofoil trailing edge modification using wedge in improving the aerodynamic performance of RAE 2822 aerofoil. It is also investigated the optimum wedge configuration that provides higher improvement of the aerodynamic performance. The calculation of aerodynamic characteristics is performed using RAMPANT program based on the Reynolds Averaged Navier-Stokes.

2. Aerofoil Transonic Flow Phenomena

Transonic flow occurs on the aerofoil surface when the flow point with Mach number equal to unity exists on the upper surface of the aerofoil. This constitutes lower limit transonic flow velocity and is known as critical Mach number. Increasing free-stream velocity above the critical Mach number the portion of transonic flow on the upper surface of the aerofoil becomes greater in downstream and forward stream. The transonic flow going to the down stream experience the decreased velocity and terminate with occurring shock wave.

Further increasing free stream velocity the portion of supersonic flow becomes greater and the position of shockwave shifts to backward and increase the shockwave strength. When flow pass to the shockwave, the flow properties such as temperature, density, and pressure become higher. Besides of influenced by free-stream condition in front of the aerofoil, the level of shock wave strength is also influenced by the flow condition in down stream behind the shockwave, that is adverse pressure gradient and boundary layer. If the shockwave interacts with the turbulent boundary layer with enough the thickness on the region of high adverse pressure gradient so the flow separation on that region will be occurred. A factor that influences the increased adverse pressure gradient and the growth of boundary layer along the downstream on the upper surface aerofoil is a flow that occurs on the trailing edge and on the wake region. While, the flow on the trailing edge and on the wake region connected with flow coming from the lower surface of the aerofoil. The pressure difference between the upper and lower surface flow on trailing edge causes flow curl from the lower surface to the upper surface of the aerofoil. This provides higher adverse pressure gradient and thicker boundary layer on the upper surface of the aerofoil.

Therefore, the pressure happened on the trailing edge becomes a key to solve the problem. Modifying the portion of the trailing edge with a given trailing edge thickness causes the coming flow from the upper and lower surfaces of the aerofoil did not meet directly on behind of the trailing edge, but on the wake region.

3. Various Trailing Edge Modifications

The modification trailing edge includes the blunt trailing edge, Gurney flap and divergent trailing edge. Each configuration is shown in figure 1.

- Blunt trailing edge is defined as the trailing edge shape with the upper surface curvature be parallel to the lower surface at the trailing edge and have a given trailing edge thickness. In 1967 the blunt trailing edge concept has been applied on the thin trailing edge of the transonic aerofoil by Whitcomb [2]. This modification provided the increased aerofoil aerodynamic performance on higher velocity and the addition of drag is relatively small. This was indicated by the present of increased circulation occur around the aerofoil and decreased pressure behind the trailing edge base. It is also explained that the present of the boundary layer growth becoming thicker when approach to the trailing edge of the upper surface aerofoil. Whitcomb noted that the present of boundary layer thickening on the trailing edge would decrease effective chamber on the trailing edge of the supercritical aerofoil [2].

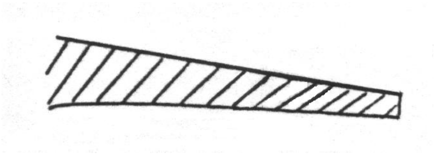

Figure 1a. Blunt trailing edge

- Gurney flap is a trailing edge shape that shaped from a plate attached vertically to chord line of the trailing edge. This idea was firstly developed by Daniel S. Gurney from the problem to improve down lift of the wing that inversely attached in front of and behind rear wheel of the racecar. The down force is intended to improve adhesion force on racecar wheels during acceleration, braking and on turning [3,4]

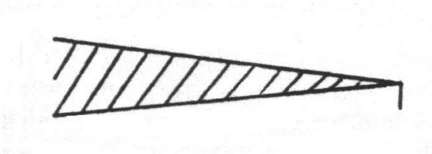

Figure 1b. Gurney Flap

Furthermore, Gurney flap idea is quantified by Liebeck on the wind tunnel test with test model of Newmann aerofoil on Reynolds number between 1.0-2.0 x 10^6 . In this testing, the Gurney flap height of 1.25 % is attached trailing edge of the Newmann aerofoil. During the test, the used wake tuff identifies streamlines from the trailing edge on the upper surface deflected to the direction of the Gurney flap and occur a backflow behind the Gurney flap modeled by two vortices. Liebeck was concluded that Gurney flap height above 2% chord provided increased drag noticeably.

- The initial investigation of Divergent trailing edge performed at Mc Donnell Douglass in 1981. It was identified three characteristic of the trailing edge providing higher aerodynamic performance compared to two preceding trailing edge types. This New Concept of the trailing edge is proposed by Henne and Greg [4].

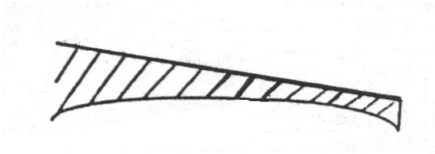

Figure 1c. Divergent trailing edge

The three basic geometry characteristics are

- The lower surface aerofoil in trailing edge region has a great curvature.
- It is required bunt trailing edge base
- A great divergent trailing edges angle between upper surface an lower surface aerofoil.

4. Methodology

4.1. Computational Approach

Aerodynamic characteristic data for analysis of aerofoil aerodynamic analysis in this research is yielded from numerical calculation. A numerical code used in this research is commercial program RAMPANT. The solver program RAMPANT has great capability in calculation such as steady and unsteady flows, compressible and incompressible flows, viscous and non-viscous flows, conduction and convection heat transfer. The governing equation solved in the RAMPANT program solver is Reynolds Averaged Navier-Stokes equations. Turbulent solution is solved by including RNG k-e and k-e turbulent model equations. This program uses finite volume method to discretize differential partial equation with time integration of the forth order Runge-Kutta

4.2. Aerofoil and Trailing-edge Wedge Models

The geometry of the RAE 2822 aerofoil and its modified version with trailing edge wedge is shown in figure 2.

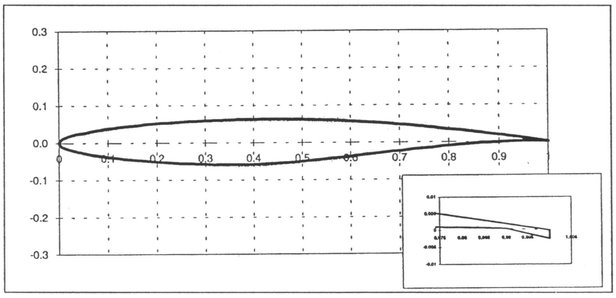

Figure 2. RAE 2822 Aerofoil and Trailing-edge Wedge

The RAE 2822 aerofoil has been chosen for a computational test for the following reasons:

- The RAE 2822 aerofoil is a supercritical aerofoil has previously has been investigated using both wind tunnels and computational methods
- The experimental database of the RAE 2822 is available for the assessment of the computational model [6].

An additional trailing-edge wedge on an aerofoil provides an increased camber in the trailing edge region and thus increased the lift of the aerofoil. The increase in camber depends on the wedge geometry, this includes the length and height of the wedge. A high camber increment is obtained by increasing the height of the wedge and/or the length of the wedge. However, experimental observation indicates that an increase in trailing edge thickness beyond approximately 0.7% of an aerofoil chord provides a significant increase in both subsonic and transonic drag levels [7]. There is also a requirement to maintain sufficient structural thickness in order to avoid large bending moment at the kink due to the aft loading. For a divergent trailing edge, the minimum thickness structural limitation is given by an aerofoil with a trailing-edge angle not greater in magnitude than –30 degree or –0.52 radians [4]. For aerofoil modified with a trailing edge wedge, the tailing edge angle can be defined as the ratio of the wedge height to its length. The length and height of the wedge considered in this study were determined based on the above considerations. Therefore, the length of the wedge for this investigation is varied by 0.5%, 1.0%, and 1.5% of the chord with the wedge height of 0.25% of the chord and 1.0%, 2%, and 3% of the chord with the wedge height of 0.5% of the aerofoil chord. The combination of the above values provides six wedge sizes as shown in figure 3.

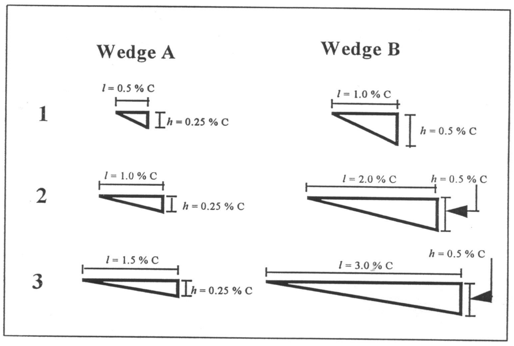

Figure 3. Six different wedge configurations attached on RAE 2882 aerofoil

4.3.Test Condition

The test condition chosen for the validation of the computational results were selected from the experimental database produced by Cook, *et. al* [6]. The test conditions considered are those of test cases 9 and 12 , see table 1.

Flow Parameters	case 9	case 12
Mach number	0.73	0.73
Reynolds number	6.5 x 10^6	2.7 x 10^6
Angle of attack	3.19^0	3.19^0

Table 1. Test Condition

In order to provide reference data with which to compare the aerodynamic performance of the modified RAE 2822 aerofoil, a computation is also performed for the following conditions.

- Angle of attack: -2.0, 0.0, 2.0, 4.0, 5.0, 6.0, and 8.0 at Mach number of 0.73
- Mach number: 0.3, 0.5, 0.6, 0.7, 0.73, 0.74, 0.77, and 0.8 at angle of attack of 3.19

Reynolds number: 2.7×10^6 and 6.5×10^6

5. Results and Discussion

5.1. Aerodynamic Performance for various attitude

- Figure 4 shows the curve of lift coefficient versus angle of attack for the original RAE 2822 aerofoil and with six additional trailing-edge wedges.

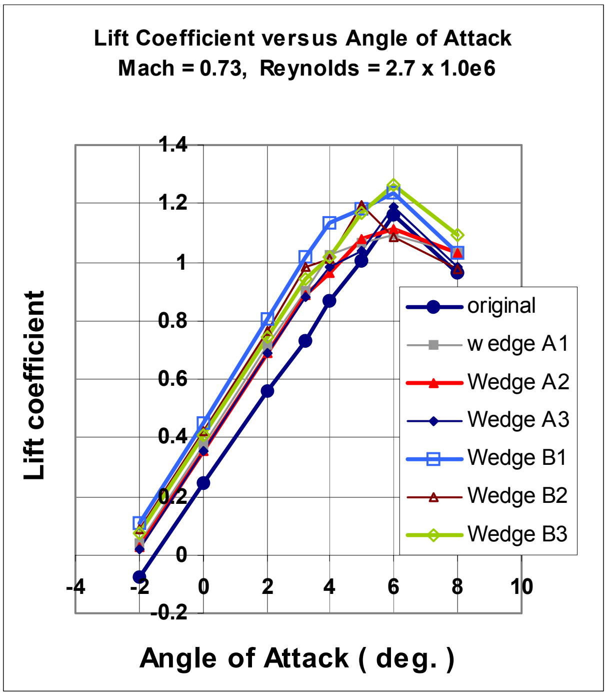

Figure 4. Lift Coef. vs Angle of attack

The amount of lift increment depends on the size of the wedge. In the linear lift slope region, the higher lift increment is obtained by increasing the wedge height and reducing the horizontal length of the wedge as shown by the wedge B1. While the higher lift increment at the maximum lift coefficient at which the viscous effect be dominant is resulted by increasing both the height and horizontal length of the wedge as shown by the wedge B3. Furthermore the reduced length of the wedge causes the stall to occur gradually as shown by wedge A1 and B1.

- Figure 5 shows the drag polar for the original RAE 2822 aerofoil and six additional trailing-edge wedges.

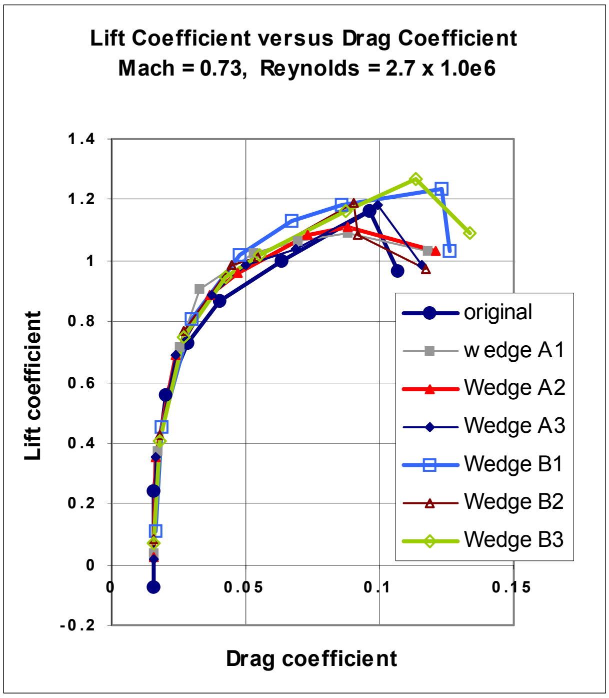

Figure 5. Lift coef. vs Drag coef.

The drag increment is strongly affected by the wedge height gives higher drag increment. At low lift coefficient, the addition of wedges increases the drag of the RAE 2822 aerofoil. This is due to the wedge not being immersed in the boundary layer. Consequently the drag increment consists mainly of base drag. At the high lift coefficient, the wedge is immersed in the boundary layer. The wedge reduces the amount of the RAE 2822 aerofoil wedge. Wedges A1, A2, and A3 which have a smaller height than the wedges B1, B2, and B3 give drag reduction at lower lift coefficient as shown in figure 5.

- Figure 6 shows the curve of pitching moment coefficient against lift coefficient. The pitching moment coefficient increases with increased angle of attack until the stall occurs. The addition of a wedge increases magnitude of the pitching moment coefficient, and it become more negative.

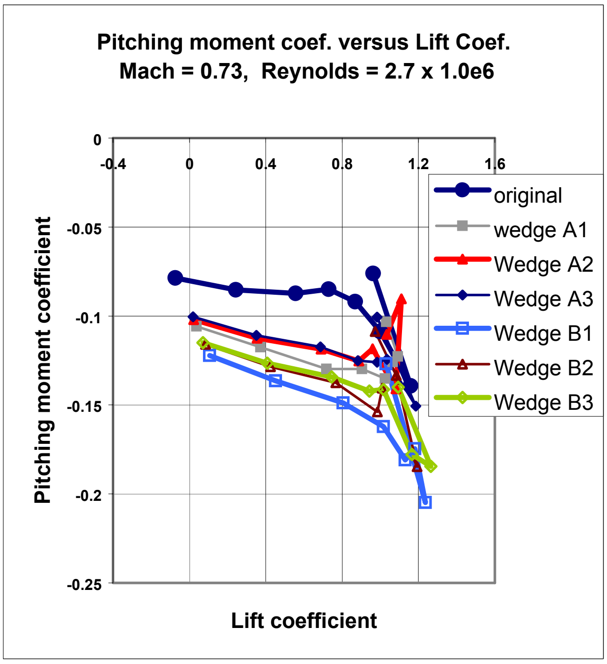

Figure 6. Pitching moment coefficient vs Lift coefficient

The pitching moment coefficient increase is caused by the additional aerodynamic loading in the trailing-edge region. Reducing the wedge height causes the pitching moment coefficient to decrease.

5.2. The optimum wedge configuration

Figure 7 shows the curve of Mach number times lift over drag coefficient for the original RAE 2822 aerofoil and with six additional trailing-edge wedges. Aerodynamic efficiency (M*L/D) is used as a criterion to determine the optimum wedge shape. As shown in figure 7, wedge A2 gives the highest aerodynamic efficiency, M*L/D = 21.07 at lift coefficient of 0.69 (angle of attack of 2 degrees). This means that wedge A2 provides the optimum shape in improving the RAE 2822 aerofoil aerodynamic performance. The optimum wedge shape is subsequently tested on various Mach number and the resulted aerodynamic performance is compared with the original aerofoil.

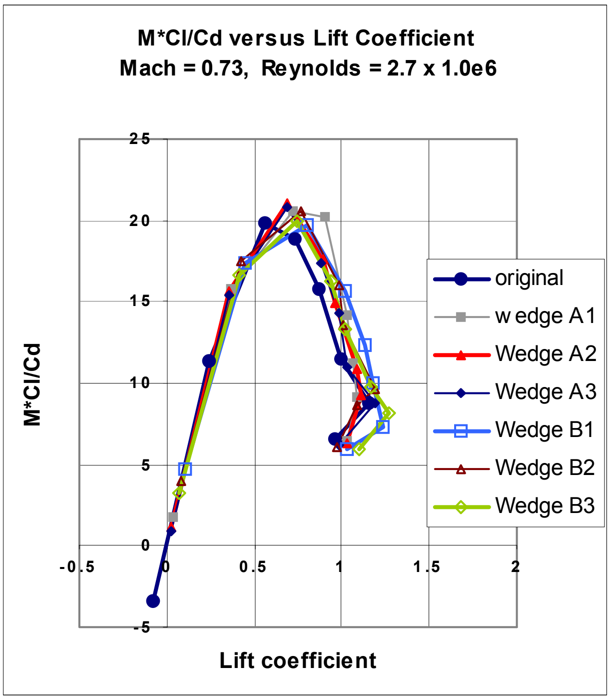

Figure 7. M*Cl/Cd vs Lift coefficient

5.3. Aerodynamic Performance for various Mach number

- The comparison of lift coefficient versus Mach number for the RAE 2822 aerofoil and it's modified with wedge A2 are shown in figure 8. The additional lift generated by the modified aerofoil is approximately 20 % of the original aerofoil lift coefficient.
- Figure 9 shows the comparison of drag coefficient against Mach number at the same angle of attack for the RAE 2822 aerofoil and it's modified with wedge A2. The presence of the trailing-edge wedge produces a slightly higher drag coefficient than the original RAE 2822 aerofoil. The percentage of extra drag due to the trailing-edge wedge increases with the increased Mach number. The largest increment of drag coefficient occurs for Mach numbers greater

than 0.7, this corresponds to the point which boundary layer separation begins at the upper surface trailing edge and then interacts with the shock waves.

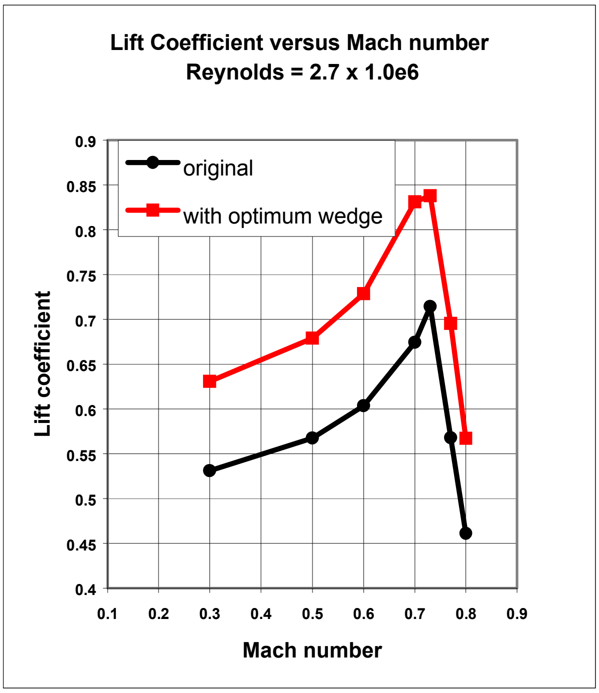

Figure 9. Lift coefficient versus Mach number

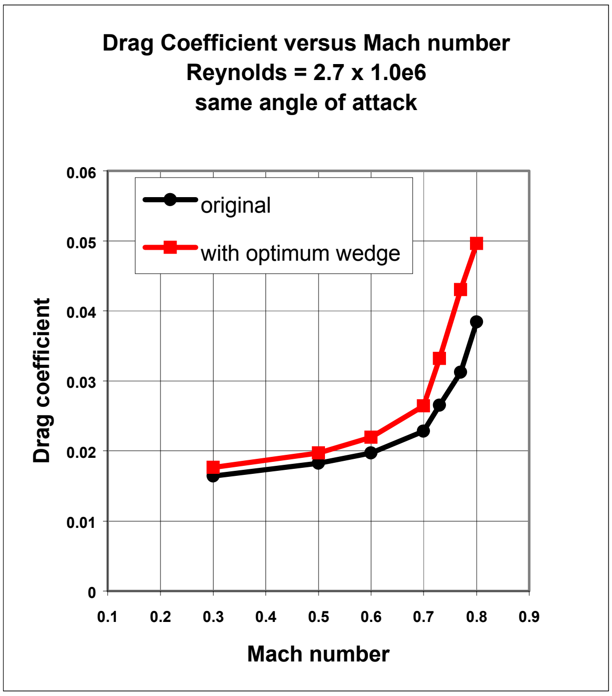

Figure 10. Drag coefficient versus Mach number at same angle of attack

- Figure 11 shows the comparison of drag coefficients against Mach number at the same lift coefficient for a given Mach number. At the same lift coefficient, the modified aerofoil with the wedge has less angle of attack than the original aerofoil. The modified aerofoil with the wedge A2 provides less drag coefficient than the original aerofoil and produces a slight increase in the drag-rise Mach number.

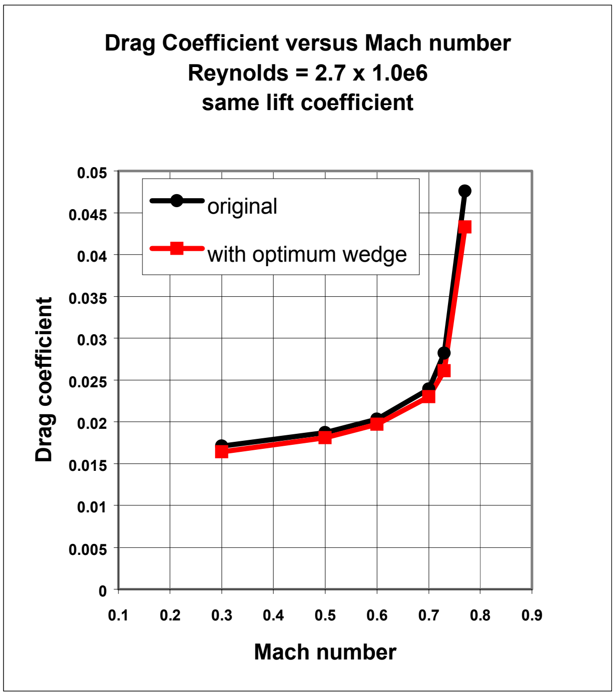

Figure 11. Lift coefficient versus Mach number

- A comparison of pitching moment coefficients versus Mach number for the RAE 2822 aerofoil and its modified with wedge A2 is shown in figure 12. This figure indicates that the addition of the wedge reduces the pitching moment coefficient over the Mach number range considered causing it to become more negative.

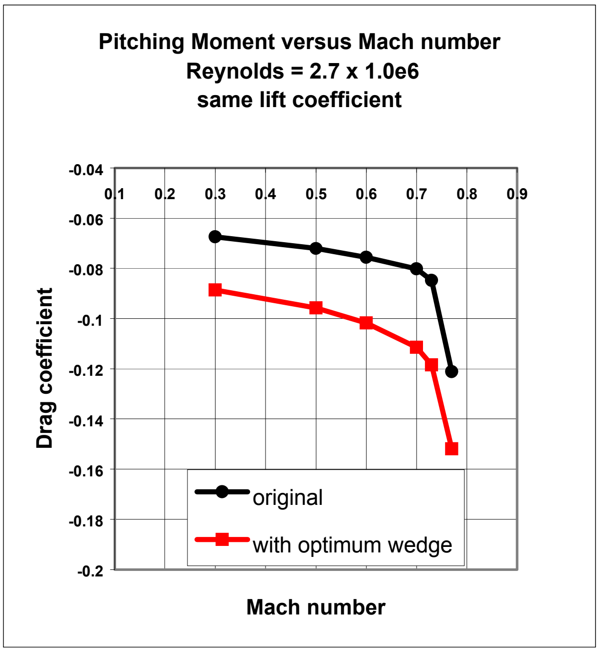

Figure 12. Pitching moment coefficient versus Mach number

- Figures 13 and 14 shows a comparison of the Mach number times lift over drag coefficient versus Mach number for the RAE 2822 aerofoil and its modified with the wedge A2 at the same angle of attack and at the same lift coefficient, respectively.

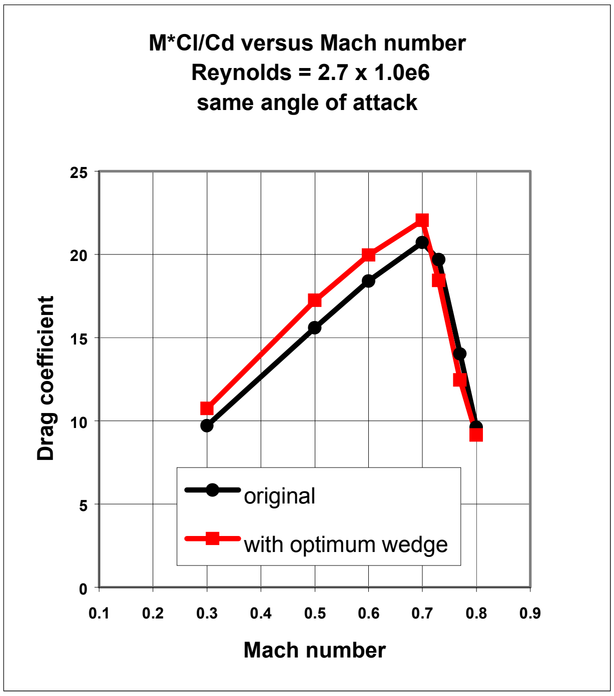

Figure 13. M*Cl/Cd versus Mach number at same angle of attack

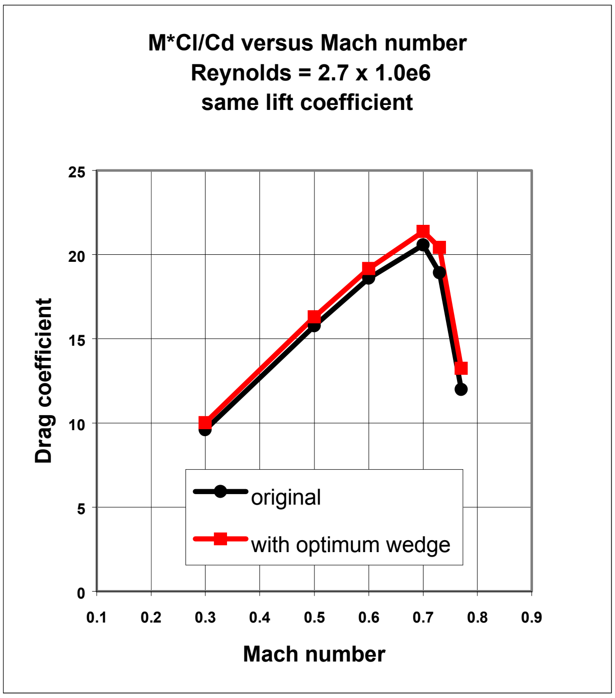

Figure 13. M*Cl/Cd versus Mach number at same lift coefficient

At the same angle of attack, the modified aerofoil with the wedge A2 produces a higher Mach number times lift over drag coefficient than the original aerofoil up to a Mach number of approximately 0.72. At the same lift coefficient, the modified aerofoil with the wedge A2 produces higher Mach number times lift over drag coefficient than the original aerofoil over the Mach number.

6. Summary

The additional trailing-edge wedges provide the improvement of the aerodynamic performance of the transonic aerofoil. The amount of lift increment depends on the size of the wedge, namely the height and horizontal length. The additional lift generated by the optimum wedge is approximately 20 % of the original aerofoil lift coefficient.

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