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AERODYNAMIC MODELLING OF A REFUELLING BOOM

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Abstract

As part of the EU FP7 RECREATE research project, a prototype boom for civil air-to-air refuelling was designed. One of the critical aspects concerns boom control in the transonic flight regime, since the RECREATE concept is based on automatic in-flight refuelling at high speed.

A preliminary aerodynamic model of the boom was created using a panel code and handbook methods. Interference and compressibility effects were analysed with RANS and URANS simulations. Possible improvements to the boom aerodynamic design were also evaluated.

1 Introduction

The RECREATE (REsearch on a CRuiser Enabled Air Transport Environment) project [1] is about improving the overall efficiency of long range air transport by introducing a feeder-cruiser system.

The idea is that large 'cruiser' aircraft would keep flying back and forth between far-away destinations for a long time without descending from their optimal cruise altitude, while smaller 'feeder' aircraft would transport passengers, fuel, baggage, supplies and waste between the orbiting cruiser and the airports. The technical and operational aspects implied by this concept are extremely challenging, but the potential fuel savings shown by the study are impressive.

A less ambitious scenario, where the feeder delivers only fuel to the cruiser aircraft, would still significantly improve long range air transport efficiency and could become reality in the near future [2]. In fact, military operations rely on air to air refuelling (AAR) to increase the range of combat or transport aircraft since the 1940's.

There are two military AAR systems currently in use, the 'probe-and-drogue' and the 'flying boom'. The latter is better suited to civil AAR operations, because it allows higher transfer rates, is less sensitive to atmospheric turbulence and is much less demanding for the pilots of the receiving aircraft. An example of a flying boom is shown in figure 1.

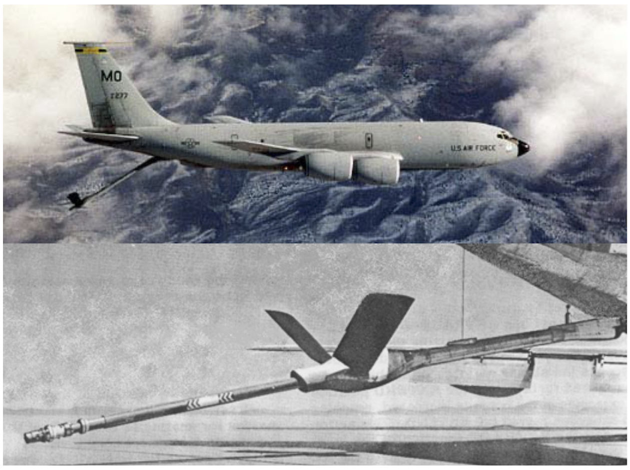

Fig. 1 KC-135 tanker and refuelling boom [3]

The rigid boom is attached below the tail of the tanker with a gimbal joint. The boom operator, who sits in the tanker's tail facing the receiving aircraft, can control the boom in pitch and azimuth by commanding the deflection of two control surfaces, called ruddervators. He also commands the extension of the telescopic part of the boom to connect it with a refuelling receptacle on the receiving aircraft. To start an AAR operation, the receiving aircraft must fly in the correct position behind the tanker, aided by optical references and by the indications received by radio from the boom operator. The formation must be accurately kept, so that the operator can safely connect the boom head to the refuelling receptacle. The area of safe contact with the boom head is known as the 'air refuelling envelope'. Pilots qualified for military air refuelling operations need to be specially trained.

In the civil AAR concept developed within the RECREATE project, the whole refuelling operation would be completely automatic, with an extremely high level of safety. There would be no need of a boom operator or of specific training for the pilots of the receiving aircraft. Moreover, it is assumed that the receiving aircraft (the 'cruiser') would not need to reduce speed below Mach 0.75 or descend from cruise altitude, as it is the case in military AAR operations. This poses some additional requirements to the boom aerodynamic design.

2 Boom design

As stated before, refuelling booms for military applications have only two control surfaces. Such a configuration has no control redundancy and is not adequate to the high system safety requirements of a civil application.

A configuration with three control surfaces has a serious drawback. If the third vertical surface is placed above the boom, it suffers from aerodynamic shading in operation and poses stowage problems. If placed below, it may limit the rotation angle of the tanker aircraft at takeoff and landing.

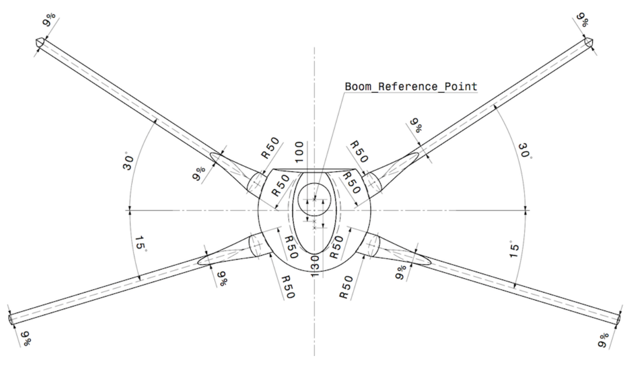

Fig. 2 Front view of the ruddervator configuration

For these reasons, a prototype configuration with four ruddervators has been selected. The two lower control surfaces have a relatively small anhedral angle of 15°, while the two upper surfaces have a dihedral angle of 30°.

Initial simulations [4] have shown that the proposed angles are adequate to control the boom within a wide refuelling envelope. The boom pitch angle Θ can be controlled between 15° to 45°, the azimuth angle from $-30°$ to 30° and the refuelling head can be extended by 6 m.

With respect to to the KC-135 boom shown in figure 1, the proposed design is about two meter longer and can extend to a maximum length of 18 m. The refuelling envelope of the boom is shown in figure 3.

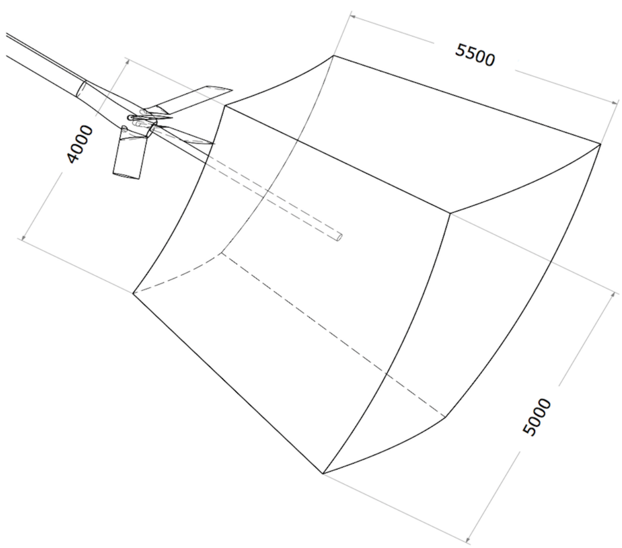

Fig. 3 Air refuelling envelope

The ruddervators of the prototype boom have a rectangular planform. They have a span of 1.6 m. a chord length of 0.5 m and 28° sweepback. The profile is a NACA 64-009.

3 Preliminary aerodynamic model

A reliable aerodynamic model is needed to perform simulations of the refuelling process and to develop the boom control laws. Obviously, it is impossible to cover all combinations of ruddervator deflections, boom position and flight Mach number, and some simplifying assumptions must be made in defining the boom aerodynamic model. As a first approximation, the force and moment coefficients due to the ruddervators (indicated by the subscripts *rv1*, *rv2*, *rv3* and *rv4*) have been calculated with a panel method, while those due to the boom shaft (subscript *b*) and to the boom extension (subscript *be*) have been estimated with handbook methods [5]. Within this approximation, the aerodynamic interference effects between the four ruddervators may be neglected, and the total force and moment coefficients can be expressed as follows:

$$
\begin{aligned}
c_x &= c_{x_b} + c_{x_{be}} + c_{x_{rv1}} + c_{x_{rv2}} + c_{x_{rv3}} + c_{x_{rv4}} \\
c_y &= c_{y_b} + c_{y_{be}} + c_{y_{rv1}} + c_{y_{rv2}} + c_{y_{rv3}} + c_{y_{rv4}} \\
c_z &= c_{z_b} + c_{z_{be}} + c_{z_{rv1}} + c_{z_{rv2}} + c_{z_{rv3}} + c_{z_{rv4}} \\
c_{m_x} &= c_{m_{x_b}} + c_{m_{x_{be}}} + c_{m_{x_{rv1}}} + c_{m_{x_{rv3}}} + c_{m_{x_{rv3}}} + c_{m_{x_{rv4}}} \\
c_{m_y} &= c_{m_{y_b}} + c_{m_{y_{be}}} + c_{m_{y_{rv1}}} + c_{m_{y_{rv3}}} + c_{m_{y_{rv3}}} + c_{m_{y_{rv4}}} \\
c_{m_z} &= c_{m_{z_b}} + c_{m_{z_{be}}} + c_{m_{z_{rv1}}} + c_{m_{z_{rv3}}} + c_{m_{z_{rv3}}} + c_{m_{z_{rv4}}}
\end{aligned}
$$

All aerodynamic coefficients are referred to the ruddervator planform area. The reference point for moment coefficients is the center of the boom gimbal joint. No compressibility effects were considered in the initial phase.

The aerodynamic coefficients representing the ruddervators' contribution are presented in three-dimensional lookup tables as a function of boom pitch angle Θ, azimuth Ψ and ruddervator deflection δ_{rv}, while those representing the contribution of the boom and of its extension are presented in two-dimensional lookup tables as a function of Θ and Ψ. For example, figure 4 shows the contribution of the ruddervator to the three aerodynamic moment coefficients as a function of deflection δ_{rv} and boom azimuth Ψ.

To evaluate transonic and interference effects, steady RANS and time accurate URANS calculations were performed with EDGE [6]. EDGE is a well known and widely validated CFD tool for compressible flows developed at the swedish national research institute FOI for the aerospace industry. The aircraft manufacturer SAAB uses it as an aerodynamic design tool for high performance aircraft.

The complete boom geometry was modelled with a high fidelity hybrid mesh with more than 20 million grid points. The boundary layers were solved directly, no wall functions were implemented. Grid convergence exercises were performed; the sensitivity to turbulence models (K-w EARSM and Spalart-Allmaras) and to the numerical scheme used was assessed in all simulations. All calculations were made with the steady state approach; some cases showing large flow separations were checked with the time-accurate approach.

For small deflections, the ruddervator lift and pitching moment coefficient calculated with EDGE are in good agreement with the results obtained with the panel method. This confirmed that the simple linear model is adequate for preliminary simulation exercises. However, the CFD analysis indicated the presence of large flow separation areas on the boom bulb and of shock waves on the ruddervators at higher deflections.

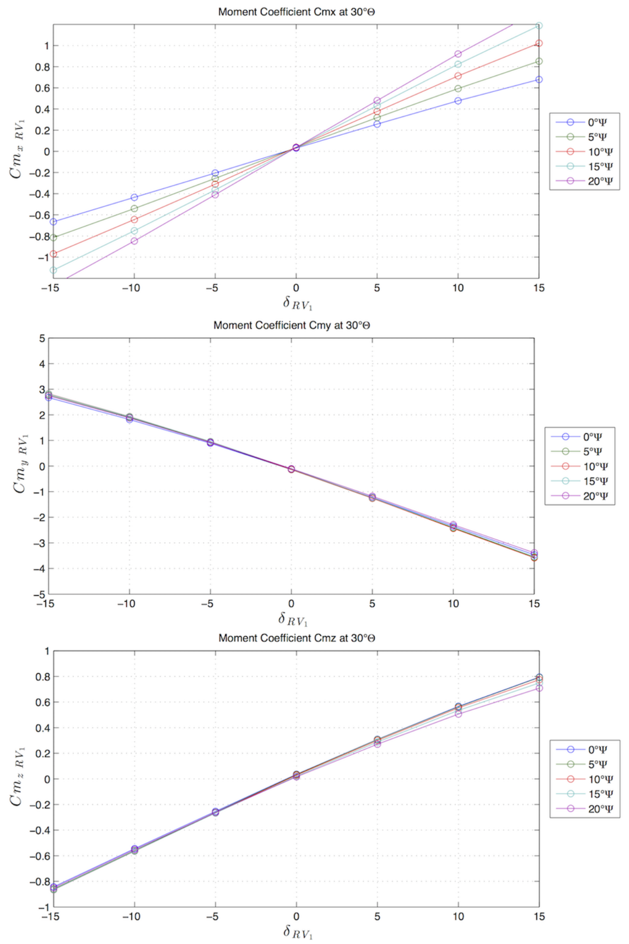

Fig. 4 Ruddervator moment coefficients versus deflection and boom azimuth

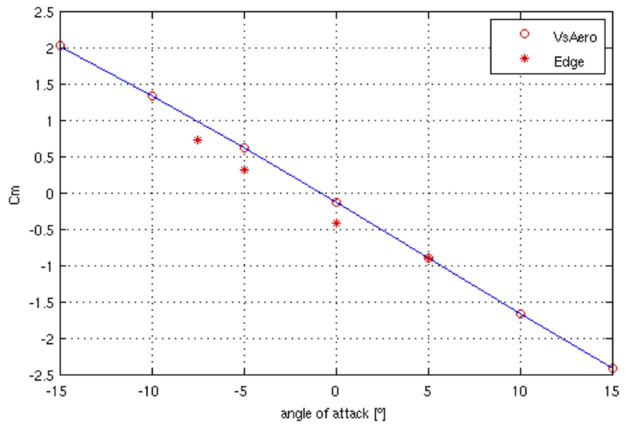

Fig. 5 Pitching moment due to ruddervator angle of attack at Mach 0.75: comparison between panel method (VsAero) and RANS results (EDGE)

4 Flowfield analysis

Figure 6 shows the result of a RANS calculation at Mach 0.75. The flow separates from the aft portion of the bulb, and a large area of unsteady vortical flow is present.

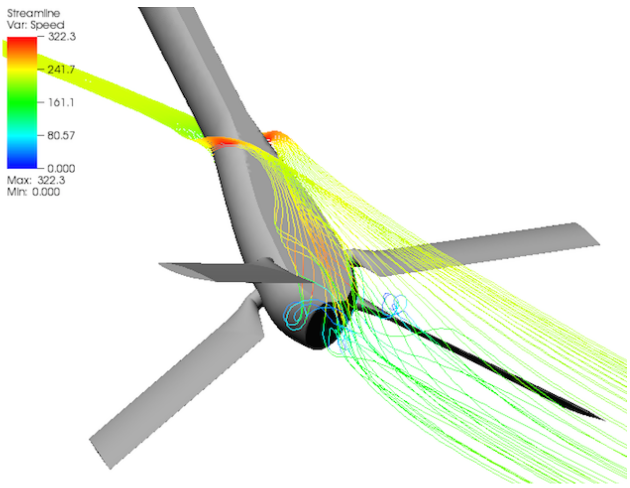

Fig. 6 Vortical flow region aft of the boom bulb at Mach 0.75. Boom pitch angle 35°, ruddervators neutral.

This appears to be the dominant flow pattern. Its unsteady character is probably the most serious issue, as it might introduce vibrations in the frequency range of the boom controls. A reduction of the Mach number to 0.65 does not change the flow characteristics significantly (figure 7).

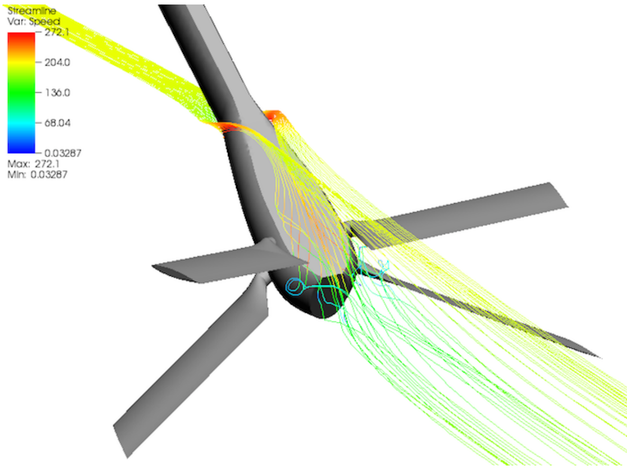

Fig. 7 Vortical flow region aft of the boom bulb at Mach 0.65. Boom pitch angle 35°, ruddervators neutral.

Figures 8 and 9 present the pressure contour lines on the boom ruddervators at Mach 0.65 and 0.75, respectively. The supersonic flow regions are shown in red.

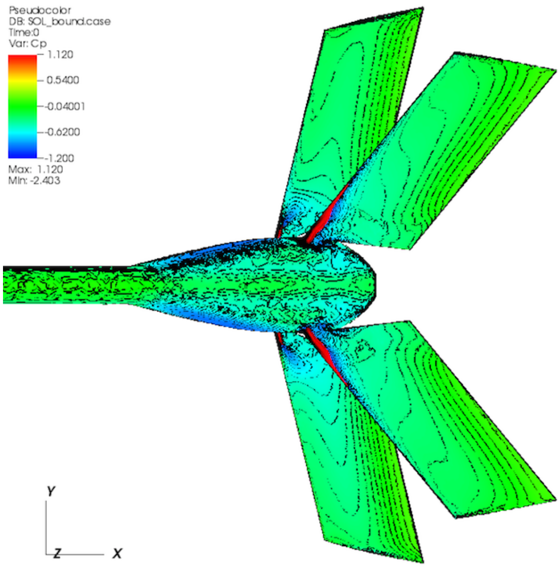

Fig. 8 Pressure contour lines at Mach 0.65. Boom pitch angle 35°, ruddervators neutral.

The flow on the ruddervators is dominated by three-dimensional effects. Shock waves do not appear on the boom mast.

Figure 10 shows what happens when one of the ruddervators is deflected by 2°, 4° and 6° respectively: the supersonic region extends outboards and the flow on the surface becomes more 'two-dimensional'.

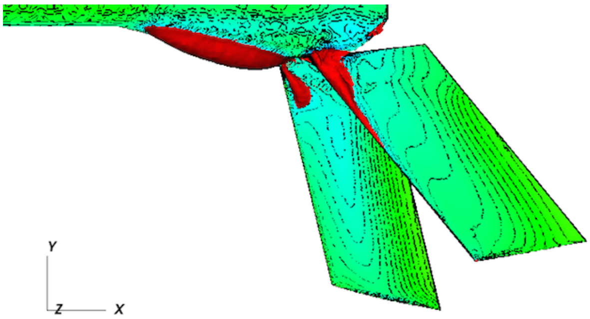

Fig. 9 Pressure contour lines at Mach 0.75. Boom pitch angle 35°, ruddervators neutral.

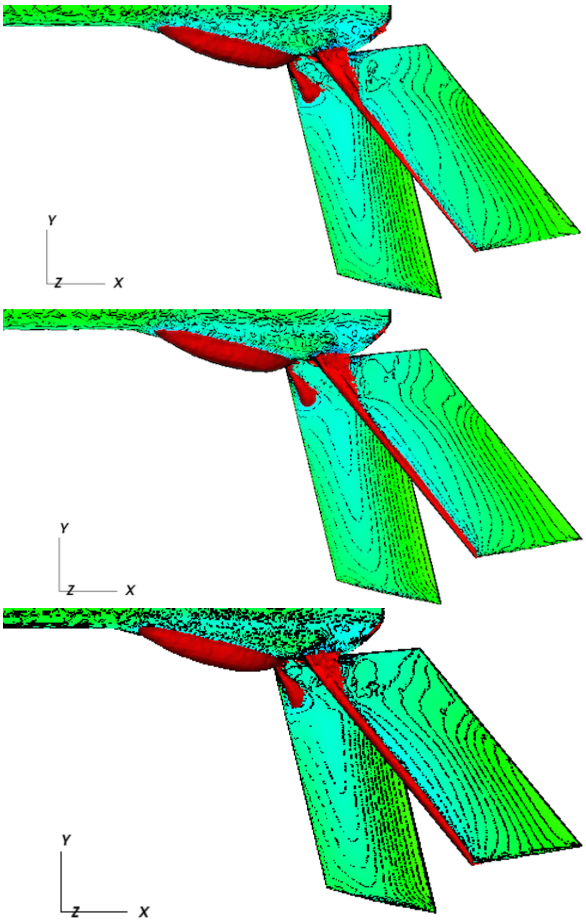

Fig. 10 Pressure contour lines at Mach 0.75. Boom pitch angle 35°, one ruddervator deflected by 2° (top), 4° (middle) and 6° (bottom).

5 Possible design improvements

Current AAR booms are designed for operation in the subsonic regime. A 'transonic' boom design is indeed much more challenging, as the CFD flow analysis of our rather conventional prototype configuration shows. The following areas for improvement can be identified:

- contain the separated flow area behind the bulb;
- achieve a wide linear range of elevator effectiveness at high Mach;
- avoid shock induced buffet phenomena on the ruddervators.

These requirements have been addressed with a simple 'sensitivity analysis' of the boom and ruddervator shape. For example, by reducing the bulb width by 10% and increasing its height by 60%, the size of the separated flow region and the boom drag are significantly reduced (figure 11).

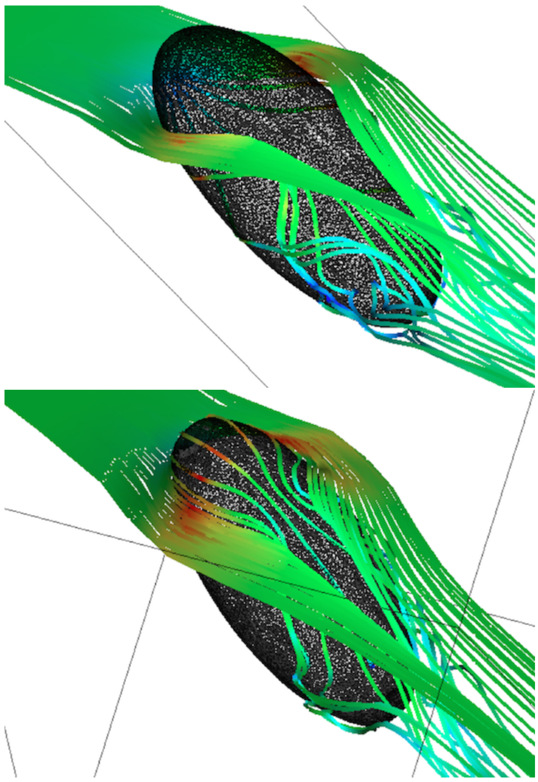

Fig. 11 Baseline (top) and improved (bottom) bulb shapes at Mach 0.75.

The ruddervator planform can be shaped to mitigate the three-dimensional effects and improve the control effectiveness at high Mach (figure 12).

Boom control by conventional ruddervators at Mach 0.75 can be problematic. The critical Mach number is reached at very small deflections

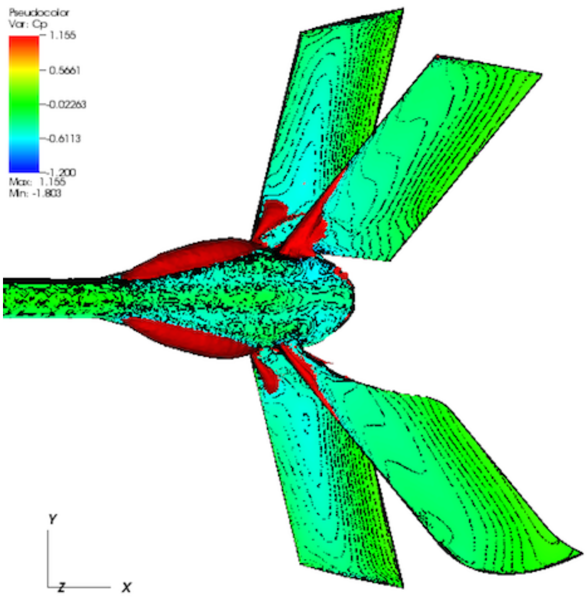

Fig. 12 Pressure contour lines at Mach 0.75, modified planform. Ruddervators neutral.

(between 1° and 2°). At larger deflections, the control effectiveness and the aerodynamic hinge moments are non linear. Shock induced buffet phenomena may occur, causing severe control interference problems.

Mini trailing edge devices (mini-TEDs) could be an interesting option. Figure 13 shows a comparison of the same ruddervator airfoil at approximately the same lift coefficient and Mach 0.75 in two dimensional flow. With a mini-TED, the ruddervator deflection can be reduced from $-4°$ to $-1°$. The maximum local Mach drops from 1.5 to 1.26, and the intensity of the shock waves is greatly reduced. The drag coefficient of the airfoil with the mini-TED is more than 40% lower. The aerodynamic efficiency is much improved, and the risk of shock induced buffet is greatly reduced. There is also the possibility of combining ruddervator deflection at lower control frequency and mini-TED deflection at higher frequency.

There are many more geometric parameters that can be changed. We have just analysed a few variants, but the results already show that there is a big potential for improvement to be exploited by an aerodynamic optimisation process.

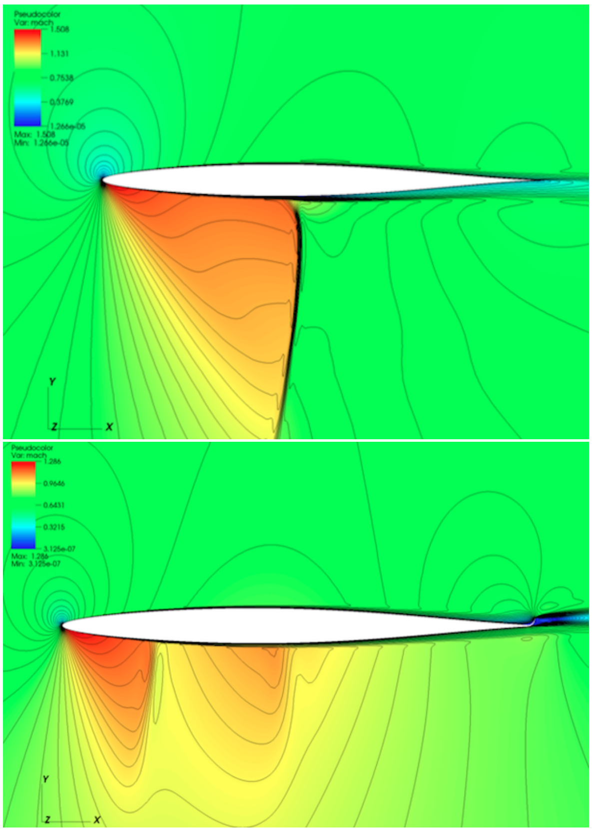

Fig. 13 Two-dimensional flow analysis on the ruddervator airfoil at Mach 0.75. Top: $\delta_{rv} = -4°$, $c_l = -0.65$, $c_d = 0.0248$. Bottom: with mini-TED, $\delta_{rv} = -1°$, $c_l = -0.70$, $c_d = 0.0136$.

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