A feasiblity study on designing model support systems for a blended wing body configuration in a transonic wind tunnel

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ABSTRACT

It is considered that the blended wing body may offer the possibility of improvements in performance efficiency over the conventional civil transport. Such configurations will require transonic wind tunnel testing. Hence, a feasibility study has been carried out at ARA to investigate possible model support systems that could be used for this purpose. The study addressed issues arising from the mechanical design of two support systems; namely, a blade or Z-sting and a standard rear sting. In particular, the relatively restricted space available within the model fuselage has presented challenges in the design of the layout of the balance and instrumentation required for the model. CFD analysis has been carried out to assess the relative interference effects of the two support arrangements. This initial work has shown unexpectedly significant interference effects associated with the Z-sting support and attention is drawn to the need for further design work to minimise these effects.

NOMENCLATURE

c aerofoil or streamwise chord.
C_D drag coefficient.
C_l rolling moment coefficient.
C_L lift coefficient.
C_m pitching moment coefficient.
C_n yawing moment coefficient.
C_p pressure coefficient.
C_S side force coefficient.
M_∞ Mach number.
x ordinate in streamwise direction.
α angle of incidence.
β angle of sideslip.
η wing spanwise position based on gross semi-span.

1.0 INTRODUCTION

This paper describes a feasibility study carried out at ARA, with support from the UK DTI, on the design of support and measurement systems for a blended wing body configuration in a transonic wind tunnel.

Various strategic reports and position papers have stressed the likelihood of the development of a blended wing body configuration as a future commercial airliner. These have included evidence presented to the Parliamentary Trade and Industry Select Committee (February 2002) and the AeIGT final report[1]. Both these documents have emphasised the need for continued research into the aerodynamics of such innovative configurations, including the requirement for experimental facilities capable of testing them. Additionally, the BAE SYSTEMS Strategic Capability Partnership has identified the unmanned aerial vehicle (UAV/UCAV) as a likely future military systems platform.

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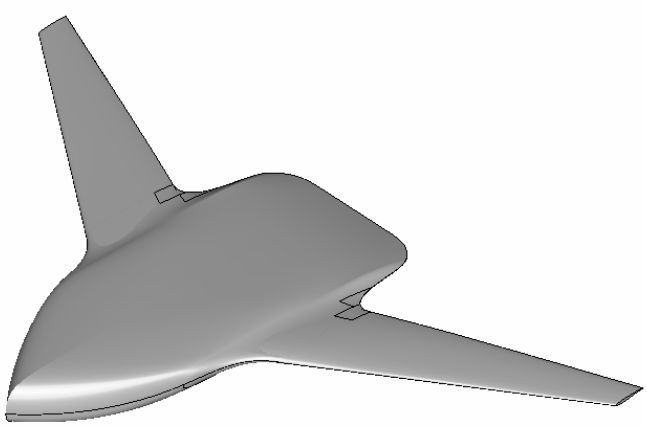


Figure 1. Blended wing body configuration geometry.

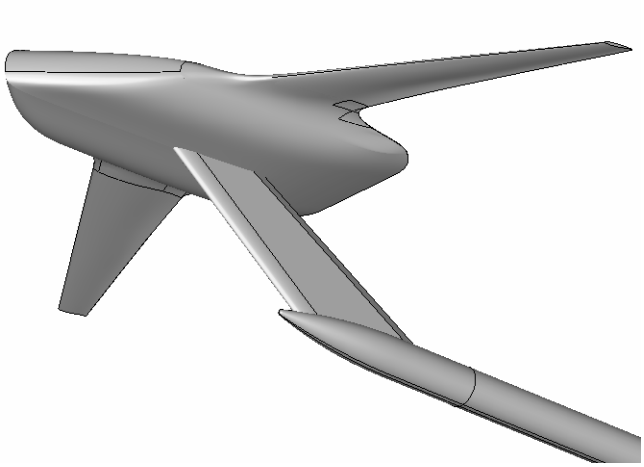


Figure 2. Model mounted on the Z-sting support.

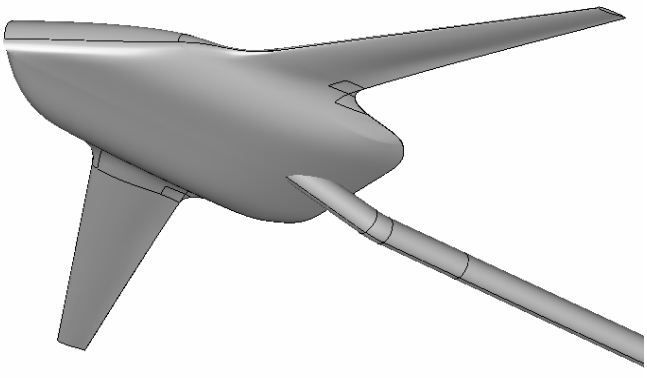


Figure 3. Model mounted on the rear sting support.

Subsonic civil transports have evolved along a line that maintains cantilever wings on a distinct cylindrical, or near-cylindrical, fuselage. As a consequence, performance and efficiency gains have been mostly incremental. Over fifty years, the sum of these gains has become substantial, resulting in modern transports that are far more economical and efficient than their predecessors. While studies indicate that more significant potential gains still exist for the conventional transport, the blended wing body offers the possibility of further improvements over and above these.

The blended wing body is an extremely integrated design, addressing technical issues in configuration design, aerodynamics, structures, propulsion and flight mechanics. Analyses of this type of configuration have indicated potential significant cost and performance benefits over projected conventional concepts. However, many challenges must be addressed before these benefits can be achieved. Major challenges include the development of structurally efficient passenger cabins that carry pressure loads in bending thick transonic aerofoil sections for the centrebody; propulsion/airframe integration; aircraft systems integration; passenger emergency egress; ride quality; and interfacing with existing infrastructure.

In order to address some of these challenges, wind tunnel testing on transonic configurations will be required. Currently, most projected blended wing body configurations are characterised by very thin trailing edges in the region of the centre of the rear fuselage with control surfaces across the entire trailing edge of the aircraft. Engines may be mounted on the upper surface of the fuselage close to the trailing edge or be semi-buried in the fuselage. These factors mean that the normal rear single sting concept of supporting the model in the wind tunnel may no longer be appropriate. Also, the blended wing body is not a configuration that lends itself to conventional half-model testing, making it probable that powered testing may need to be performed on a full model.

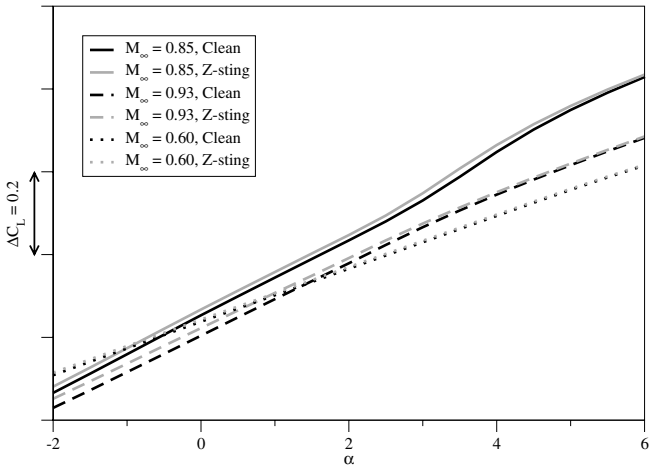
The purpose of this feasibility study was to consider the possible requirement for a new support system for blended wing body wind tunnel model configurations and to recommend appropriate solutions to the difficulties of performing transonic wind tunnel tests. The study was carried out with reference to testing in the ARA transonic wind tunnel (TWT). At the outset of the project, it seemed probable that two alternative support systems would be required to enable both performance and stability and control testing to be carried out. To this end, two candidate support systems were considered: a blade or Z-sting arrangement and a standard rear single sting.

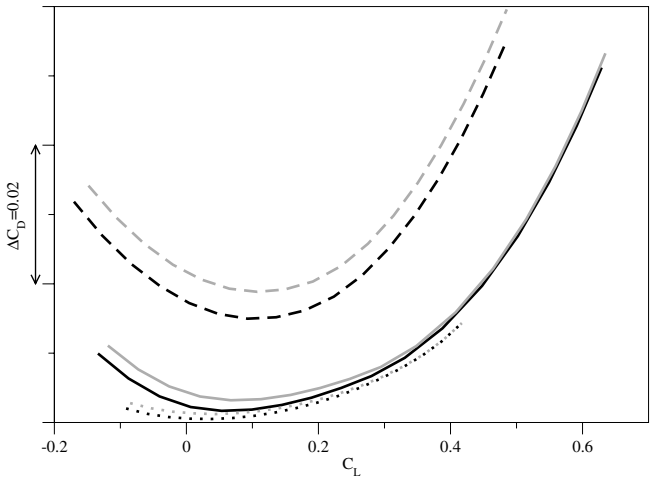
It was initially considered that the use of a standard rear sting would require significant distortion to the model lower surface in order to ensure that the upper surface remained unmodified and, hence, this arrangement would not be suitable for performance testing. In contrast, a Z-sting arrangement was considered appropriate for performance testing, though not for stability and control testing as the interference effects of the blade would be unacceptably large at non-zero sideslip angles.

The study included the mechanical design of the proposed model support systems and the CFD analysis of a representative aircraft model with and without the various supports. The practical constraints imposed by the need to maintain the structural integrity of the support systems and to ensure adequate space for instrumentation within the model and the support systems were taken into account in the analysis and this is described in section 2. The interference effects of the support assemblies on the model determined using CFD analysis are discussed in section 3.

Some consideration was given in the study to the issue of powered testing, although the detailed design and analysis of any possible approach was beyond the scope of the project. The approach adopted at ARA for conventional powered testing is to use a half-model, equipped with air-driven turbine powered simulator (TPS) units, mounted on an under-floor balance. An alternative technique may be needed for a blended wing body configuration, particularly with engines mounted on the upper fuselage.

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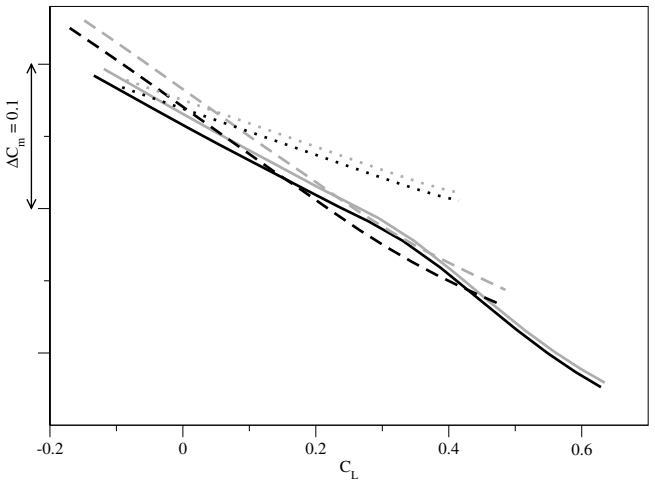
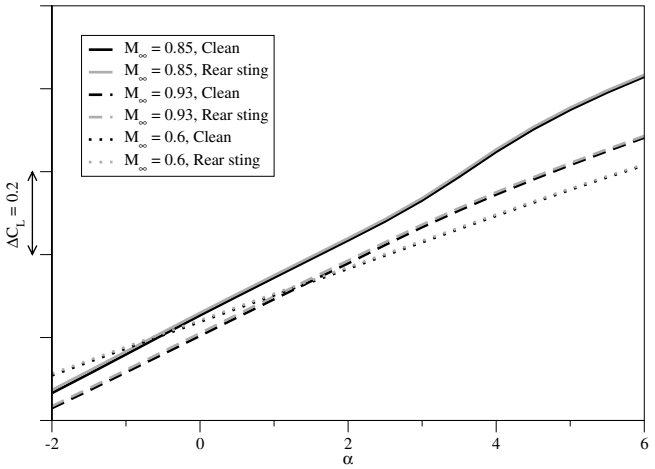
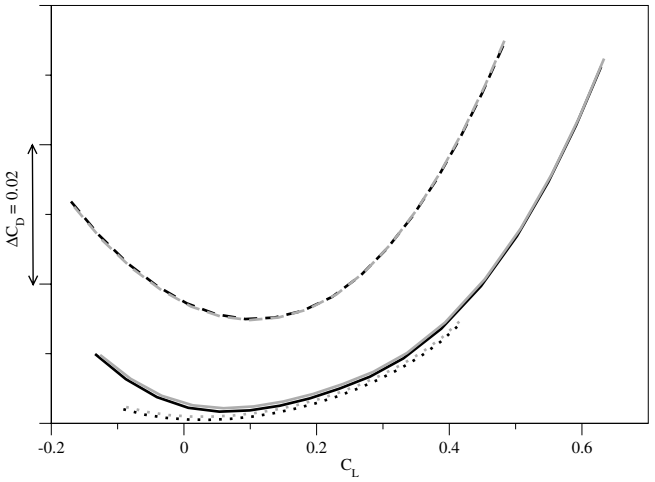


Figure 4. Comparison of the lift, drag and pitching moment coefficients for the clean and Z-sting models.





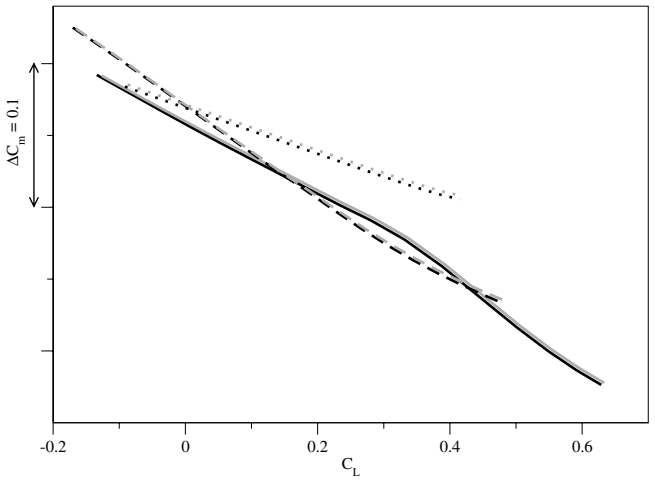


Figure 5. Comparison of the lift, drag and pitching moment coefficients for the clean and Rear sting models.

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2.0 AIRCRAFT MODEL AND MODEL SUPPORT SYSTEMS

The geometry was designed configurationally without aerodynamic optimisation by Airbus UK and supplied to ARA for the purposes of the research project. The aircraft geometry represents a conceptual mock-up configuration with passenger and cargo space for 750 passengers and is illustrated in Fig 1. For this project, a 'clean' aircraft, i.e. without engines, vertical control surfaces and wing tip devices, was assumed. The blended wing body concept has a relatively large wing span, compared to the fuselage length and depth, and this introduces some constraints in the design of a wind tunnel model. In particular, the relatively small fuselage depth compared to a conventional civil transport with a cylindrical body would be expected to present difficulties in the model design. In this instance, the full-scale aircraft has a wing span of 99.6m and a fuselage length of 56m. The full-span model was scaled to be of comparable size to other large models tested in the ARA TWT and this implied a model scale of 1/60th. The resulting model geometry therefore had a wing span of 1,660mm and fuselage length and depth of 932mm and 90mm, respectively. The configuration was designed for a cruise condition of $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8$, $C_L = 0{\cdot}3$ at an altitude of 35,000ft.

For the majority of full-span stability and control model tests in the ARA TWT, the standard balance utilised is the ARA 3" (76·2mm) diameter 6-component balance. However, for this configuration, the depth of the model fuselage is such that there is insufficient space to accommodate this balance within the model and, therefore, the ARA 2¼" (57·15mm) diameter 6-component balance, which is used as standard for performance testing, was required.

CFD analysis of the unsupported aircraft model was performed to provide the aircraft forces and moments required to determine the model aerodynamic centre and the maximum expected balance loads. Ideally, the balance centre should lie at the aerodynamic centre of the configuration; however, the size of the model dictates that the balance centre has to be placed further forward as there is insufficient depth in the rear part of the model fuselage to accommodate the balance and adapter. At this position, sufficient clearance could be provided within the model fuselage to prevent the balance earthing due to deflections at maximum load.

An existing Z-sting geometry was used for the initial mechanical design, this sting having been used at ARA in the past for various tests. Model geometry considerations and the initial CFD analysis indicated that the blade/fuselage junction should be positioned as far forward as practically possible to reduce the unfavourable interference effects on the flowfield around the model rear fuselage. This necessitated a redesign of the balance adapter. Figure 2 illustrates the model mounted on this support arrangement. Subsequent CFD analysis showed that the flow around the Z-sting/fuselage junction region might be improved by redesigning the blade profile, as discussed in section 3. In the redesign, the sting thickness was maintained to provide sufficient internal space for the routing of services to the model.

For the conventional (rear) sting arrangement, the design incorporated a sting entry point on the lower surface of the aft fuselage in order to minimise surface deformation, as shown in Fig. 3. The upper surface remains unmodified as future use of the model might include the addition of vertical fins or engines in this region. The sting was designed with a crank feature to permit entry into the lower fuselage to meet the 2¼" balance joint, whilst maintaining an acceptable approach angle.

Stress and deflection calculations were performed for both support arrangements and sufficient sting clearance was incorporated into the design of the fuselage components. The positioning of the balance slightly ahead of the aerodynamic centre of the model helped to ensure that the rate of change of sting incidence with cart angle is within acceptable limits.

An important driver for the model support design was the need to ensure commonality in as many model parts as possible for the two support arrangements. In order to facilitate easy access to instrumentation, both for model assembly/rigging and for ease of model changes during testing, the upper fuselage of the model was designed to be removable with fixing screws accessible from above. Adequate space was allowed within the model for all the standard instrumentation that would be required. This included an incidence meter; PSI modules for surface pressure measurements; and wiring for wing buffet gauges. Given the nature of the configuration, allowance was made for a relatively large number of pressure tappings on the wings and fuselage.

The mechanical design of the model has been carried out assuming the simple configuration shown in Fig. 1. Some thought has been given to designing the model in such a way as to allow, for example, alternative wing designs or modifications to the fuselage profile to be accommodated easily and rapidly during a test campaign. Further detailed design is required to assess the possibility of attaching flaps, vertical fins and engine mountings and their associated instrumentation.

3.0 CFD ANALYSIS

Throughout the study, the Airbus FLITE3D code was used to perform inviscid (Euler) CFD analysis. Viscous effects are probably significant in certain regions but inviscid modelling was assumed to be adequate in this initial study. As the geometry was not aerodynamically optimised, the analysis was carried out solely to assess the interference effects on the aircraft model of the model support systems proposed. To this end, calculations have been performed over a range of incidences for three Mach numbers: the cruise condition, $M_\infty = 0{\cdot}85$; $M_\infty = 0{\cdot}93$; and $M_\infty = 0{\cdot}6$, these latter representing the likely extremes for a transonic test campaign for a civil transport aircraft. Comparisons in the form of lift, drag and pitching moment coefficient polars are presented here for the each of the model support arrangements with the 'clean', i.e. unsupported, model in Figs 4 and 5. The moment reference point in the calculations is taken as the balance centre.

From the comparisons in Figs 4 and 5, it can be seen that the effect of the Z-sting arrangement on the model forces is greater than that of the rear sting, particularly at the higher Mach number condition. It is also apparent that the variation of the incremental differences between the forces over the incidence range is more consistent for the rear sting arrangement with the increments increasing with reducing incidence for the Z-sting.

A comparison of the pressure distributions for a number of spanwise stations on the three configurations is shown in Fig. 6 for the cruise condition. It can be observed that the rear sting has very little effect on the pressure distribution except close to the sting entry point. In contrast, the Z-sting produces a strong lower surface shock which affects the pressure distribution out to about 30% span, where the body blends into the wing. The blade/fuselage junction is positioned sufficiently far forward to ensure that the trailing edge pressure is unaffected by this lower surface shock. However, the Z-sting has had an impact on the wing upper surface pressure causing the shock to move downstream and increase in sweep. The reasons for this are not clearly understood, though part of the explanation may lie in the nature of the upper surface pressure distribution. This configuration exhibits a double shock pattern on the wing upper surface; this type of flow is highly sensitive to small changes in circulation, which may result in the shock movement observed in the current calculations. This in turn may cause the point at which the two shocks coalesce to change its spanwise location. A mesh sensitivity check was carried out to establish if lack of grid independence was the cause of the unexpectedly large effects. A finer mesh improved the shock definition slightly and moved the point at which the two upper surface shocks coalesce further inboard but had no other significant effect on the flow solutions.

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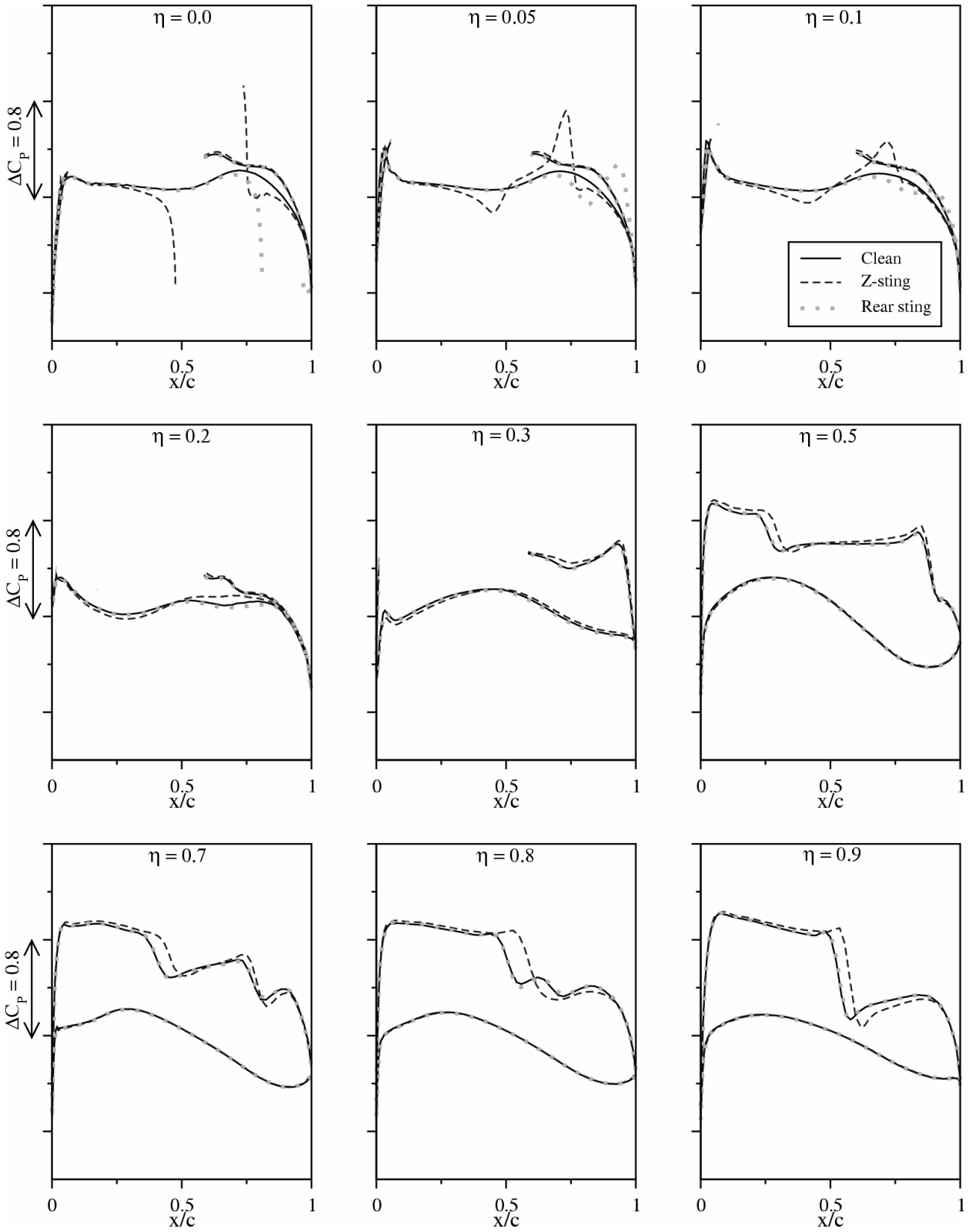
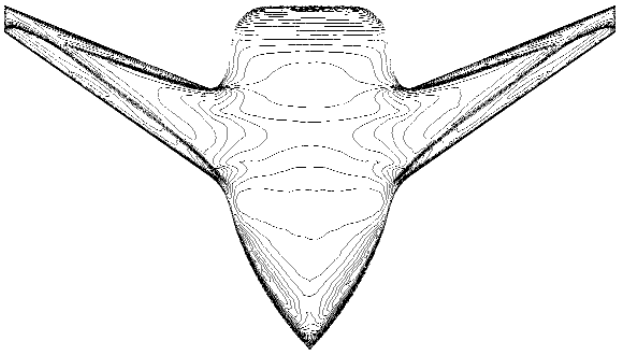
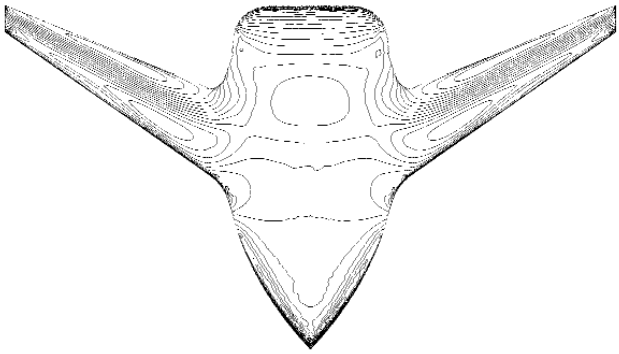


Figure 6. Pressure distributions $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$.

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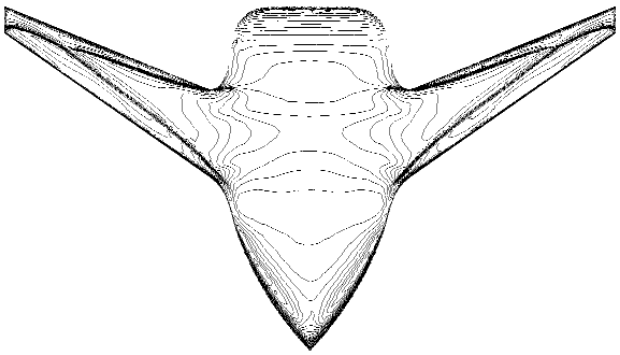


Upper surface

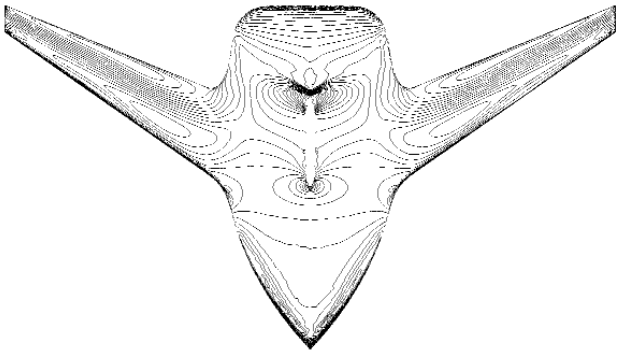


Lower surface

Figure 7. Clean model – pressure contours – $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$.



Upper surface



Lower surface

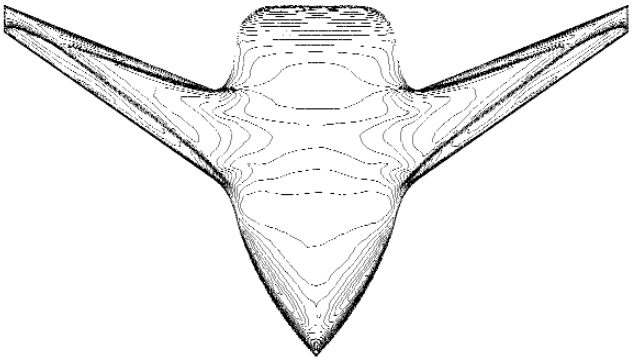
Figure 8. Model with Z-sting support – Pressure contours – $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$

Figures 7 to 9 illustrate the pressure contours for the three configurations. The slight change in the shock pattern with the Z-sting is not obvious, though careful comparison does reveal that the spanwise position at which the two shocks coalesce has moved slightly inboard. Clearly apparent is the extent of the lower surface shock emanating from the fuselage/blade trailing edge junction.

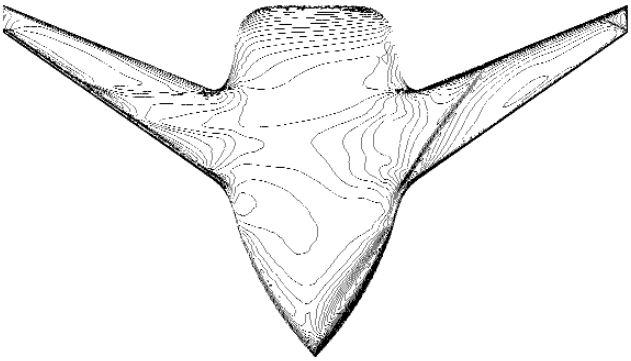
The original presumption in the study was that the rear sting support arrangement would be a candidate for performing stability and control testing, whereas the Z-sting could be used for performance testing as its interference effects at non-zero sideslip would be unacceptable. To confirm the suitability of the rear sting for stability and control testing, calculations were carried out for a range of sideslip angles and the results compared with those for the unsupported model. Surface pressure contours are shown in Fig. 10 for the model upper surface at $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$, $\beta = 10°$, and these show that the flow patterns for the two configurations are similar. Figure 11 shows comparisons of the force and moment coefficients for the three Mach number conditions. The yawing and rolling moments at $M_\infty = 0{\cdot}93$ are of opposite sign to the results at the lower Mach numbers. This is due to the formation of a shock on the lower surface of the port wing, which reduces the lift on this side of the model, hence causing positive moments.

Given the unexpectedly large interference effects on the configuration of the Z-sting arrangement, a short exercise was carried out to redesign the blade profile with the intention of reducing these effects. The original Z-sting strut did not represent the most aerodynamically optimised shape, being basically a fairing to cover the internal structure, with the same section applied over the entire length of the blade. Within the time constraints of the project, it was only possible to investigate a simple profile shape change. The new shape was designed to satisfy the structural stress requirements of the model support and with sufficient internal space for the routing of services for the model down the leading edge of the strut, whilst having a more aerodynamic shape. Figure 12 shows a comparison of the section geometry and of the pressure distribution between the new and original blade sections at a location halfway between the model lower surface and the aft sting adapter. The pressure distributions for the cruise condition at a number of spanwise stations are also shown in Fig. 12. The results indicate that although the flow over the blade has been improved with the new section, the occurrence of a strong shock, albeit slightly weaker, at the blade/model junction still persists and the upper surface pressure distribution is still affected by the presence of the sting. These results suggest that

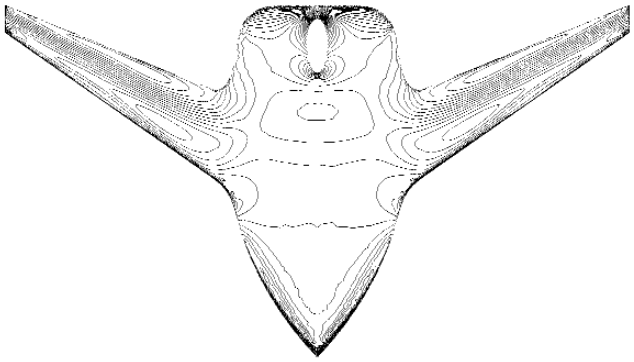
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Upper surface

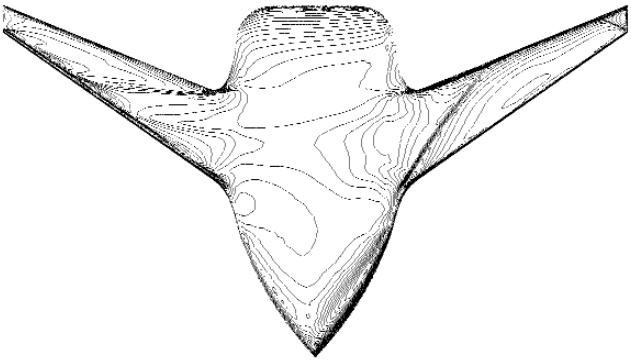


Clean model



Lower surface

Figure 9. Model with Rear sting support – Pressure Contours – $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$.



Model with rear sting

Figure 10. Pressure Contours for Model upper surface – $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$, $\beta = 10°$.

the presence of this shock at the junction may be difficult to avoid. This is an important conclusion since the flow in this region may influence both the flow over the aft part of the fuselage and the spanwise development of the flow across the wing.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The project described in this paper considered the mechanical design of two model support systems for testing blended wing body configurations in the ARA TWT. The design study included the positioning of an appropriate balance within the model and considered the implications for balance and support stressing inherent with this type of configuration. CFD analysis provided information on forces and moments which directly influenced the support design. The interference effects of the two support systems were also analysed using CFD. During the course of the exercise, a number of issues arose and these are summarised below. It should be noted that the conclusions drawn here are closely associated with the actual geometry used for the design analysis. This geometry is unlike some configurations often depicted as future concepts, such as the flying wing. Other types of conceptual design may lead to different conclusions about possible wind tunnel test techniques.

The principal findings from the study are:

(a) The initial concept was that a blade or Z-sting arrangement would be best suited to performance testing, as the model/support junction could be positioned away from the trailing edge region, which may incorporate full-span control surfaces. As this type of model support would be unsuitable for stability and control testing due to unacceptably large interference effects at high incidence and sideslip, a conventional rear sting could be used in this instance. The Z-sting concept has been somewhat brought into question as the CFD analysis has predicted significantly larger interference effects than for the rear sting, an unexpected result. It is unclear from the analysis if this conclusion would hold for a different model geometry with a different flow development and this requires further investigation. Also, alternative designs for the blade should be considered, for instance modifications to the blade sweep (perhaps locally in the vicinity of the model) and length as well as further redesign of the external profile. The rear sting design in this study has not resulted in

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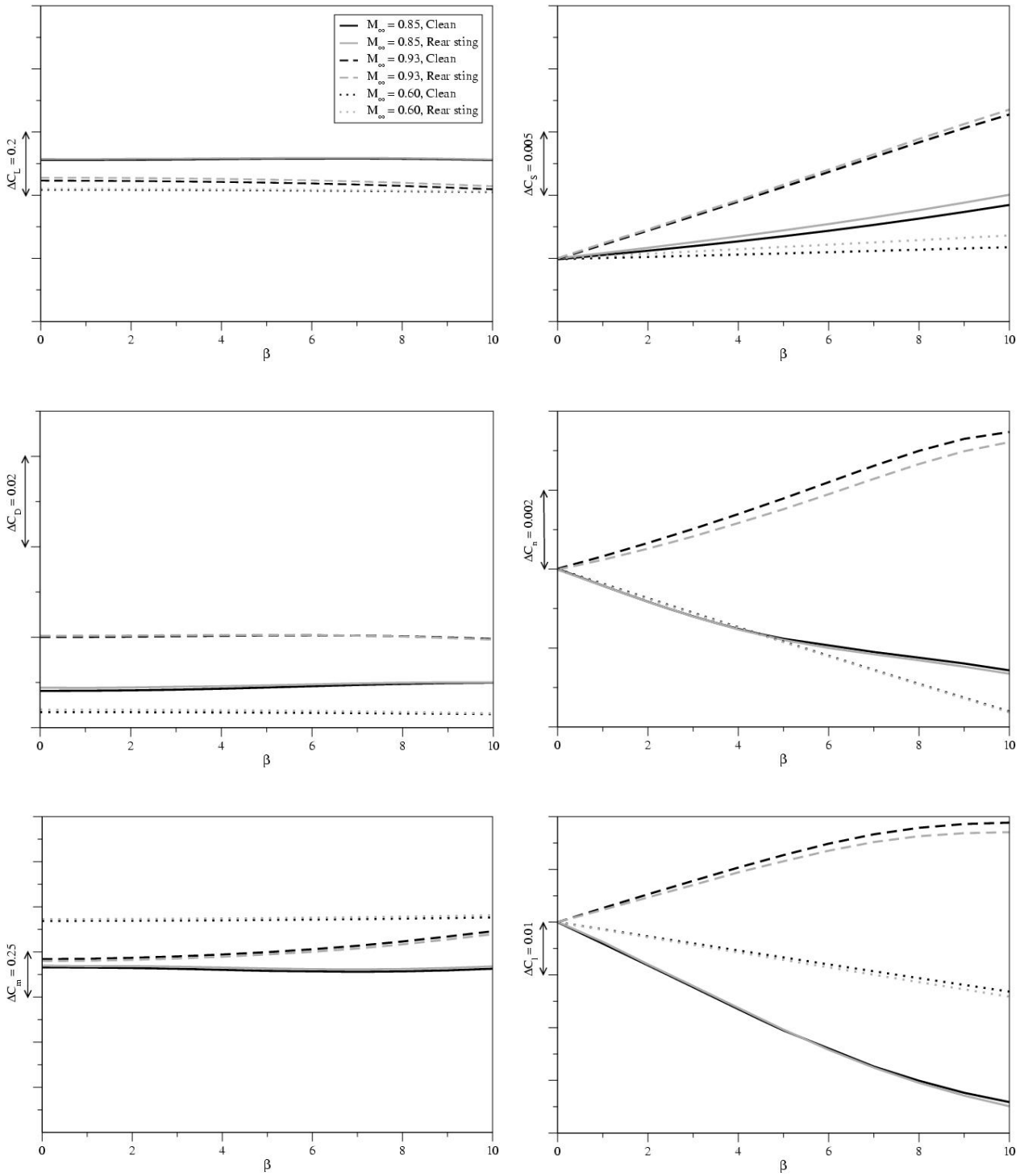


Figure 11. Comparison of force and moment coefficients for the clean and rear sting models, $\alpha = 2{\cdot}8°$.

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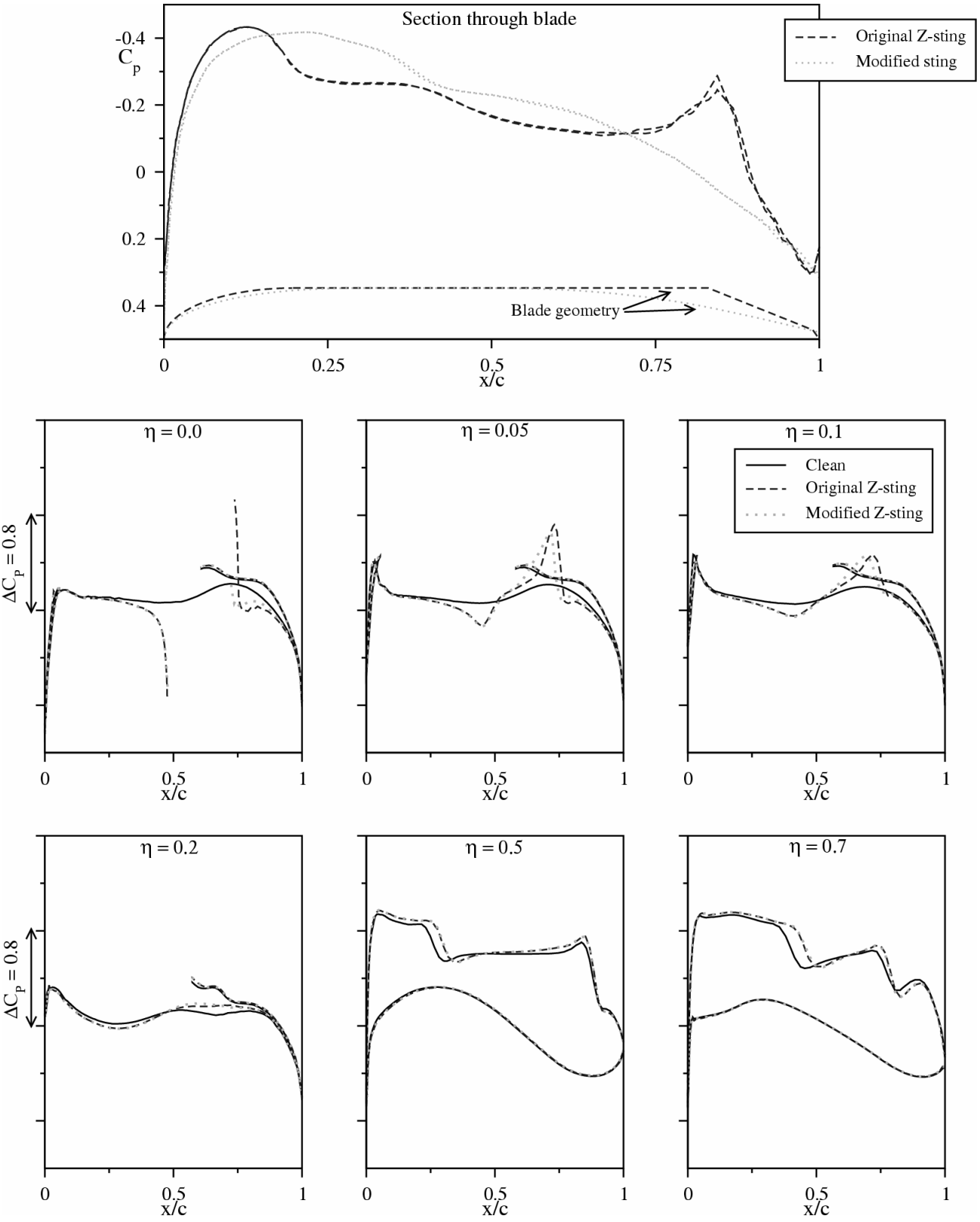


Figure 12. Comparison of pressure distributions for the original and modified Z-sting models $M_\infty = 0{\cdot}85$, $\alpha = 2{\cdot}8°$.

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significant distortion of the model and could be considered for performance testing, provided that control surface deployment at the fuselage trailing edge is not required.

b) This type of configuration has a relatively small model depth compared to a conventional civil transport model. This constraint has dictated that only the ARA 2¼ (57·15mm) diameter 6-component balance, which is standard for performance testing at ARA, can be accommodated within the model with adequate clearance. This balance does not have the high load capacity required for stability and control testing. Hence, consideration should be given to the provision of a high load capacity balance of appropriate size for this type of application.

c) The CFD analysis performed in the current exercise has been purely inviscid (Euler). For the future development and improvement of model support systems and interference correction techniques, the routine application of viscous calculations should be considered. Also, particularly for relatively large-scale models, the capability of performing calculations that include the tunnel wall effects should be established.

d) Further research is required to establish a suitable approach to powered testing. As conventional half-model testing is probably not appropriate, given the likely engine configuration, the possibilities for full-span model testing, with TPS units, needs to be explored. Consideration must be given to the efficient utilisation of the limited space available within the model and support to contain the necessary instrumentation and services for the model. Additionally, it would be necessary to understand the particular difficulties associated with semi-buried engines, which are a possibility for future concept studies.

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