OVERCOMING THE CHALLENGES OF DESIGNING, MANUFACTURING AND TESTING CRYOGENIC WIND TUNNEL MODELS

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Abstract

A collaborative research programme known as ATTACH 2000 (Advanced Turbulent Technology Applied to Civil transport aircraft – High speed) was conducted by Airbus UK and the Defence Evaluation and Research Agency (DERA) investigating aspects of high Reynolds number aerodynamics. The programme, part funded by the Department of Trade and Industry under the CARAD (Civil Aircraft Research And Development) programme, involved testing state-of-the-art wing designs optimised for different Reynolds numbers.

The requirement was to test different wing designs on a common fuselage, each extensively pressure plotted. The model was to be tested in the DERA 8ft high-speed wind tunnel, Bedford and in the European Transonic Wind Tunnel (ETW), Cologne.

Cryogenic models such as these present many challenges and during design, manufacture and testing phases of the project, several problems were encountered and overcome. This paper will discuss experience gained on items such as:

- *Designing for cryogenic conditions*
- *Achieving model build repeatability and interchangeability*
- *Instrumentation for cryogenic conditions*
- *Achieving strength requirements*
- *Finite element analysis and stress calculations*
- *Tolerance requirements for cryogenic models*
- *Installation of pressure plotting*
- *Transition band application*
- *Vibration problems with models of this type*
- *High speed testing*

1 Introduction

Up until the arrival of ETW, aircraft designers were faced with the problem of not being able to extrapolate aerodynamic data obtained in wind tunnels using scale models in order to confidently predict performance at flight Reynolds numbers.

With the construction and commissioning of ETW during the early 1990's, focus turned to high Reynolds number wing design and Airbus UK in collaboration with DERA and part funded by the DTI, established a research programme known as ATTACH 2000. The objectives of the ATTACH 2000 programme are:

- To design and test a conventional (6.3 million Reynolds number) wing design, a 40 million Reynolds number wing design and an 80 million Reynolds number wing design.
- To evaluate appropriate CFD methods and associated high Reynolds number wing design.
- Establish credible, well understood and viable techniques for wind tunnel testing high Reynolds number in order to make best use of conventional and cryogenic wind tunnels.
- To obtain a high quality database of wind tunnel data which can be used to improve current tunnel to flight extrapolations.

The programme, which was established towards the end of 1995, was split into two phases. Phase I included the design, manufacture and testing of three full span models, sharing the same fuselage and representing a very large aircraft configuration. The full span models extend the test capability up to a Reynolds number of 40 million. Phase II, which is currently in the manufacture stage, includes the design and manufacture of a half model capable of being tested up to a Reynolds of 80 million.

The programme relied heavily on experience gained during the design, manufacture and test in ETW of a 1/22 scale A320 full span model which was used in two test campaigns as a co-operative test between Airbus UK and ETW as part of the Early Collaborative Test Conditions (ECTC) programme. The objectives of these tests were to gain early experience in the cryogenic testing facility and to obtain and assess the quality of force / moment and pressure data over a wide range of tunnel conditions.

2 Model Design

2.1 Full Span Model Specification

The requirement was for a wind tunnel model representing the wing, fuselage and belly fairing corresponding to a large capacity civil transport aircraft with a high cruise Mach number. The model was to consist of:

- a single fuselage of non circular section with a detachable forward and rear body
- three interchangeable pairs of wings each of which consisting of a single integral component of port and starboard wings and lower fuselage panel incorporating a belly fairing and wing/fuselage junction fairings

The model with the three wings would have the same features in common:

- cryogenic testing capability (down to 110 Kelvin at 3.5 bar)
- wing planform
- 245 pressure tappings in each pair of wings at identical locations

2.2 Material

Material selection in the design of any wind tunnel model is a very important parameter but cryogenic wind tunnel models have the additional consideration of requiring the ability to be tested over a large temperature range.

This statement may, at first, seem fairly simplistic but in reality this implies several things:

- Strength is required over the entire temperature range

- Fracture toughness is required over the entire temperature range

- Machineability must be maintained

- Consideration of thermal expansion and contraction rates must be taken.

Maraging steel is the most widely used material for cryogenic wind tunnel models, especially for pressure-plotted models or those with nacelles and pylons fitted which produce critical sections. Other materials include austenitic stainless steels, inconel, titanium, aluminium and brass.

Maraging steel is generally available in four grades 200, 250, 300 and 350 (this denoting their nominal yield strengths in psi x 10^3). The fracture toughness of grades 300 and 350 is too low for cryogenic wind tunnel model applications and so only 200 and 250 grades are suitable. In the UK grades 200 and 250 are also known as G90 and G110 (this denoting their nominal yield strengths in tonf/in^2). Maraging steel is relatively easy to machine and has a simple heat treatment process [1].

250 grade has been used for balances but 200 grade is generally used for models and this is indeed the material selected for the ATTACH 2000 models.

2.3 Early design concepts

The starting point for design of the ATTACH 2000 full span models relied heavily on the experience gained by Airbus UK and ARA in the design of the A320 model and on development work commissioned by ETW [2].

The A320 model was designed with no external fixings on the fuselage. In order to achieve this, the model was constructed with essentially four main components:

- A single one piece wing with integral lower central fuselage
- One piece front fuselage
- One piece rear fuselage
- Central upper fuselage

All four components were assembled using long studs which were fixed into the front fuselage and which went right through the centre portions. Retaining nuts were then fixed onto the other ends of the studs inside the rear fuselage, pulling all of the components together. Access to the nuts was by way of special tools inside the sting cavity.

It was felt for the ATTACH models that, although this provided an elegant design solution for achieving no external fixings, a compromise could be made to ease model assembly (especially due to the requirement for three wing designs to be tested). As a result, the concept of using long studs was retained but they were designed to be fixed before fitting of the rear fuselage. The rear fuselage was then fixed in place with external fixings. The resulting holes were then filled using the fusible alloy Cerrobend which has a melting point of 343K and can be applied using a soldering iron. This filler is then worked using abrasive brass tools since brass is significantly softer than maraging steel but harder than the filler material.

Wing design on the A320 model used the concept of a single removable trailing edge section and a single removable leading edge section with lap joints down which pressure plotting tubes could be routed. Chordwise routing of pressure plotting tubes was achieved by drilling / Electro-Discharge Machining (EDM) into each of the required wing sections and this removed the need to cut surface slots in the wings. The trailing edge was then fixed to the wing with screws and the holes filled using a commercially available strain gauge adhesive known as X60. X60 is used as a more permanent filler than Cerrobend.

This method of construction was found to be satisfactory and was adopted and evolved for the ATTACH wings. It was found however, that during hand finishing of the A320 wings the trailing edge fixation holes exhibited some ‘dishing’ effect which, when filled, resulted in ‘feather edges’ being produced in the filler material. This problem was overcome during manufacturing of the ATTACH wings by plugging the holes during hand working and working the plugs along with the wing components thus providing a sharp hole edge as shown below.

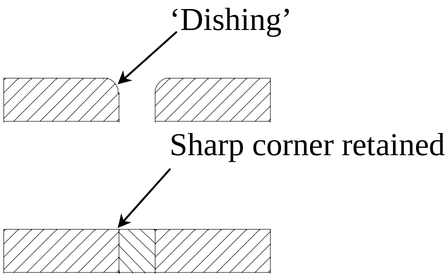

Figure 1. Removal of ‘dishing’ effect around holes using plugs.

2.4 Final design concept

The final design consisted of, in essence, nose, rear fuselage, top cap and three interchangeable wings, integral with the belly fairing and lower centre fuselage.

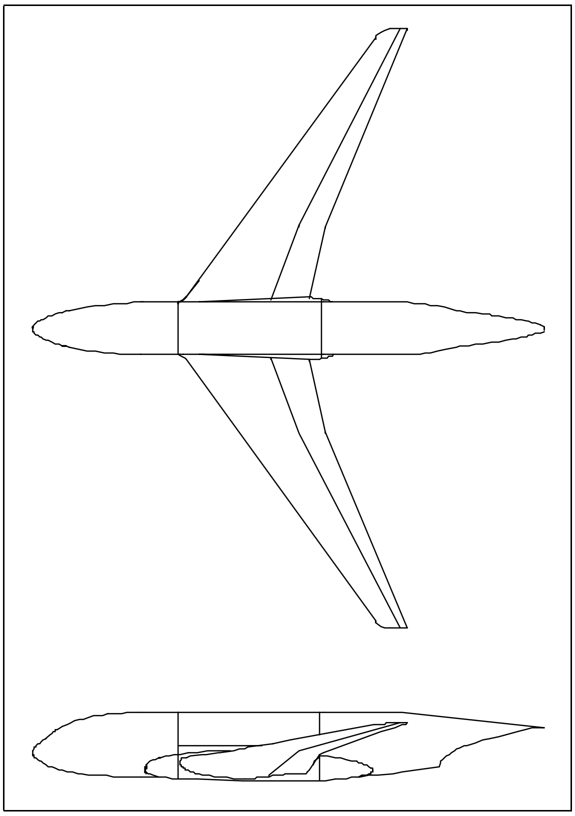

Figure 2. ATTACH 2000 full span model general assembly

A great deal of attention was paid to the housing of instrumentation, in particular with regard to changing one fully pressure plotted wing to another. Multi-way disconnects were used to facilitate ‘quick’ changes and these had to be housed inside the heated, insulated area in the nose. Space inside the nose was at an absolute premium and it was essential that each of the three wing pairs were assembled in exactly the same way each time. In order to achieve this a fixture was manufactured by ARA to ensure that the three wings were fitted with exactly the same tube lengths. Within the heated package urethane pressure tubing was used up to the disconnects with FluoroEthylenePropylene (FEP) tubing used in the unheated areas of the model from the disconnects to the metal tubing in the wing. Heat is provided by means of two 53Ω and two 11.6Ω aluminium, foil backed, Kapton insulated heater foils applied to the aluminium support bracket for the PSI modules. Two PRT 100 type temperature sensors are also fitted in this area.

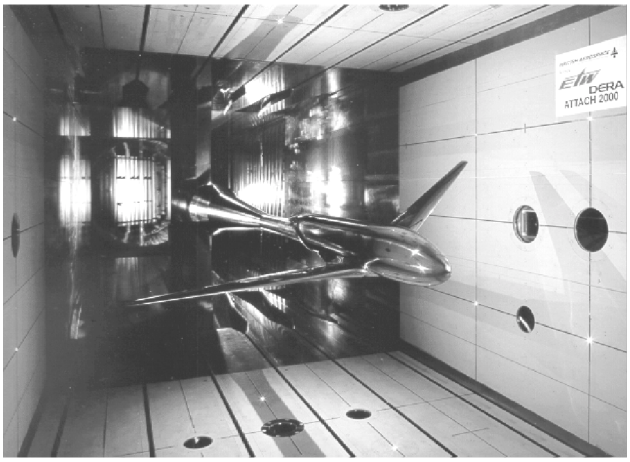

Figure 3. ATTACH 2000 full span model in ETW

2.5 Model Stressing Considerations

For testing in tunnels that have previously been routine for this type of model, standard engineering bending theory is employed to determine model strength. Safety factors of 3 on yield strength and 4 on ultimate tensile strength are the normal factors to adhere to.

The ETW model design handbook demands that for all components where structural design optimisation is important, Finite Element Methods (FEM) should be employed to allow for reduced safety factors. Safety factors of 2 on UTS are then permissible.

Airbus UK and ARA considered that for the type of construction involved on the ATTACH model it was not practicable to rely solely on FEM, especially trying to model with sufficient resolution, the stress concentration effects around the very small diameter pressure plotting holes.

As a result, in addition to finite element analyses, Airbus UK constructed a model representing the wind tunnel model wing from epoxy resin (Araldite CT200) which was covered, in localised areas, by a photoelastic coating. The model was manufactured at the same scale as the wind tunnel model with internal cavities and full chord section as for the FEA mesh model. The model was then loaded using dead weights based on five point loads, which were also used in the finite element analysis.

The primary method adopted for the evaluation of the model critical stations wing strength was the photoelastic method with the FE analysis being used as a correlation to add confidence in the results of the photoelastic exercise.

Initially a spreadsheet method using standard engineering bending theory was used to evaluate which of the pressure plotting stations gave the highest stress value. The highest two stations were then modelled using FEA. The photoelastic model was then loaded to compare with the FEA results. Pressure tappings were then put into the photoelastic model and the maximum stresses determined. Throughout this exercise an integral trailing edge was assumed. Finally an estimation of the reduced strength due to the detachable trailing edge was made.

The initial calculations identified stations 2 and 3 as the two weakest stations. The comparison of the maximum stresses (no pressure tappings) using the photoelastic and FEA methods at the two stations gave a reasonable correlation, 9.4% difference at station 2, 3.7% at station 3 with the photoelastic method giving the higher values. After insertion of the pressure tapping holes, it was found that the maximum stress had almost doubled at the critical station. This value, along with an estimated 60% efficiency in the contribution of the trailing edge to strength was then used to determine a safety factor of 2.3 on UTS.

3 Model Manufacture

3.1 Basic Model Fabrication

Each pair of wings with integral belly fairing and lower fuselage was machined from a single billet of 200 Grade (G90) maraging steel. A single piece detachable trailing edge was incorporated into each wing panel to facilitate installation of the pressure plotting. Each component was machined in stages down to within +0.6mm of the final finished surface profile with the material in the solution treated (annealed) state. The components were then heat treated to achieve the required tensile strength/fracture toughness characteristics. Following heat treatment they were finished machined to 'size' and then finally handworked to achieve the required swept surface profile tolerances as shown in Table 1.

Table 1
Wing Tolerances/Surface Finish Requirements.

Surface Profile

X/C =	0.0 to 0.2	± 0.013 mm
X/C =	0.2 to 1.0	± 0.024 mm

Surface Waviness ~ max. slope criteria

X/C =	0.0 to 0.2	0.0025 (1 in 400) over gauge length of 6.5mm
X/C =	0.2 to 1.0	0.0050 (1 in 200) over gauge length of 6.5mm

Steps in Surface
± 0.013 mm

Surface Roughness

X/C =	0.0 to 0.2	Ra = 0.10 µm
X/C =	0.2 to 1.0	Ra = 0.15 µm

The challenge in the final assembly was to provide near seamless repeatable joints between the three wing sets and the common fuselage components. This was achieved by careful design and manufacture of highly repeatable interface joints between each component. No fillers were required to meet these demanding requirements.

3.2 Wing Inspection.

Each wing was inspected by means of a combination of leading edge templates and chordwise Co-ordinate Measuring Machine (CMM) scans at 10 spanwise inspection stations. The accuracy requirements for the wings necessitated extreme care when re-establishing the datum positions for repeat CMM scans. This proved to be an extremely difficult task and some refinement of the routine inspection process was required before repeatable (better than 0.02mm) scans could be produced. Each wing surface was also CMM scanned from root to tip at 15% and 75% chord of the trapezoidal planform.

3.3 Pressure Plotting

Pressure plotting was installed in the wings after they had been handworked to achieve acceptable surface profile accuracy.

Seven internal chordwise holes were Electro- Discharge Machine (EDM) plunged in each wing panel at each of the specified pressure plotting stations.

Tubes were then installed at each of the chordwise positions (35 per station distributed between the port and starboard wing panels) running to the trailing edge joint and then inboard to the wing root.

With the exception of the pressure tappings at or close to the trailing edge all tubes were run inside the wing removing the need for any slots in the swept surfaces.

All the wing instrumentation was routed through holes in the lower fuselage exiting at the forward interface of each wing set. The tubes were then terminated at a series of disconnects to facilitate easy connection to the tubes exiting the heated package located in the model nose. Care was taken to ensure commonality, in terms of disconnect positioning, between all three wings to facilitate rapid wing changes.

4 Testing

4.1 ETW test envelope

The test envelope which was adopted in order to meet the objectives of ATTACH 2000 Phase I is shown in figure 4. Test conditions ranged from 3.6 million Reynolds number to 40 million Reynolds number. The tests were carried out at 4 temperatures and a variety of pressures with transition fixed and free.

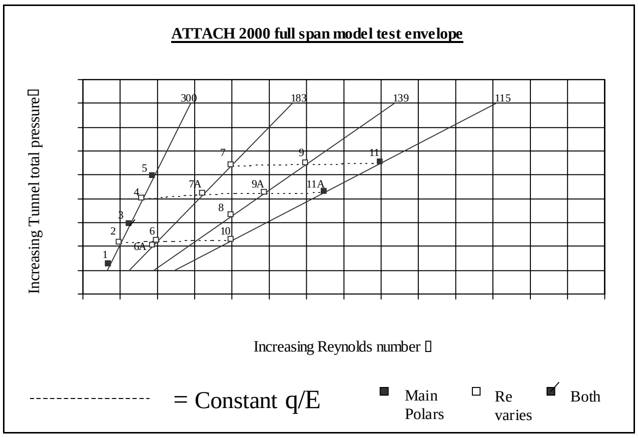

Figure 4. ATTACH 2000 full span model test envelope

This test envelope enabled the tests to be carried out, not only over a range of Reynolds numbers but also

- at a constant Reynolds number with varying dynamic pressure, q

and

- at various Reynolds number with a constant q/E (E being the modulus of elasticity) at low and high dynamic pressures.

4.2 Transition Fixing

Going right back to the basics of wind tunnel testing techniques, as Reynolds number increases, flow would be laminar up to a point where the growth of instabilities will cause transition i.e. adverse pressure gradients or shocks. If a wind tunnel model wing is tested at low Reynolds numbers and transition is allowed to occur naturally, the flow over the wing would have significant areas of laminar flow.

Transonic flow, with shocks not fixing transition, will be unrepresentative of full-scale flight. With uncertainty as to where transition occurs there will be difficulty in interpreting the data.

This problem can be overcome by applying a ‘transition band’ to the wing surfaces to force transition to occur at a particular position. By positioning the band at a further aft location the boundary layer conditions can be altered enabling the simulation of higher Reynolds number conditions, more representative of full scale aircraft.

Transition bands on transonic wind tunnel models are typically applied using small glass balls called ballotini in some kind of adhesive. The size and density of the balls and the width and position of the band are all parameters which can be varied to produce the desired results. Experience has resulted in standard transition bands being adopted for various low Reynolds numbers.

If the transition band is undersized and transition is not properly fixed then the transition front will move leading to difficulty interpreting the data (uncorrectable data). Conversely, if the band is oversized, transition will occur in the right place but the band will contribute parasitic drag due to its roughness. These phenomena are termed as underfixing and overfixing.

With a cryogenic wind tunnel model, test conditions vary from low to high Reynolds numbers and appropriate transition bands need to be employed.

4.3 Problems encountered

Model vibration was a problem throughout the test campaign. The initial model configuration, which utilised ETW's balance B003, was found to be extremely lively at all conditions. It was, in fact, very difficult to find a 'safe' point to which the model attitude could be returned upon experiencing excessive vibration. Some ambient polars were attained, although cut short, but it rapidly became apparent that most of the required test envelope would be unachievable with this arrangement as the dynamic pressure was increased.

A modal analysis (impulse hammer) was performed on the test assembly and it was found that several characteristic frequencies (or harmonics of those) were coinciding.

Several options were discussed such as adding mass to the model or moving the model forward on the sting by inserting a spacer between the end of the sting and the balance. The solution that was finally executed was to change the balance from B003 to balance B002, which was a stiffer balance. This indeed improved the situation greatly and most of the test envelope was then completed. Modal analysis of the model on the rig with balance B003 showed that a pitching frequency of 24 Hz, displacement in the Z axis of 8 Hz and wing root bending of 49 Hz. By changing the balance the frequencies were de-coupled such that the resulting pitch oscillations were eliminated.

Subsequent to changing the balance, four polars obtained with balance B003 were repeated with B002 as a check on the repeatability and were found to repeat very well (within 1 drag count at cruise).

Although greatly improved, the problem of model vibration returned especially at high dynamic pressures at high Reynolds numbers and it was apparent that the Eigenvalues were again becoming coincident at low temperatures.

This phenomenon was included in an AIAA paper presented by ETW [3].

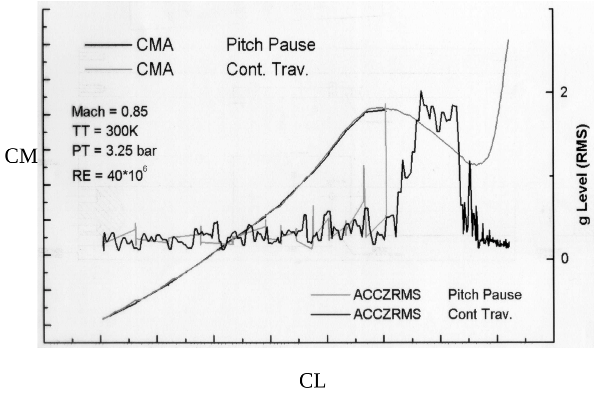

Figure 5. Model dynamics at high Reynolds number.

The plot shown in figure 5 shows graphically the dynamics of the model. A tri-axial accelerometer was fitted in the inclinometer unit and this shows the output from the accelerometer in the Z-axis superimposed over the C_M vs C_L curve. Accelerations over 2g are evident. With the continuous traverse technique it was possible to drive through this condition however, when using the pitch pause technique, the oscillations could develop to an unacceptable level and the polar had to be curtailed.

Balance B002 has a slightly lower load range than balance B003 but this proved to be a limiting factor on only one occasion.

The vibrations encountered at high tunnel total pressure led to the introduction to the test envelope of conditions 7a, 9a, and 11a at a reduced q on a constant q/E line based on the q/E at condition 4 (see figure 4).

In addition to this, test condition 5, which was initially at a Reynolds number of 10 million and was the condition upon which the constant q/E line for conditions 7, 9 and 11 was based, could not be achieved due to a tunnel power limit. The Reynolds number for this condition had to be reduced to 9.5 million and this led to the introduction of test condition 6a to retain an opportunity to study variation in dynamic pressure at a constant Reynolds number. Test condition 5 could also only be tested with ETW's second throat in the unchoked condition and at that time the Mach number stability was greatly reduced in this mode of operation as illustrated by figure 6. Subsequent control system modifications have significantly improved the Mach number control.

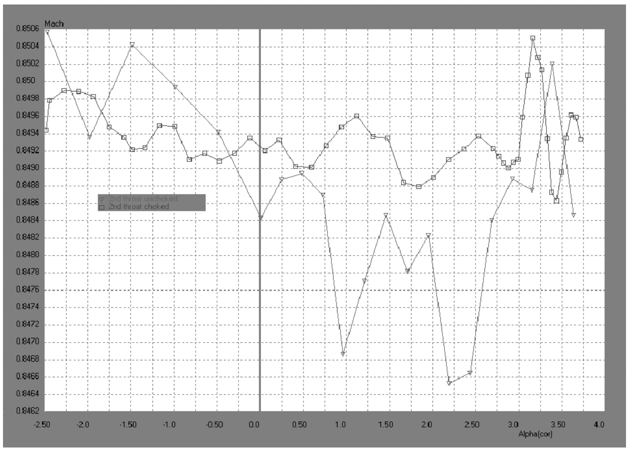

Figure 6. Comparison of Mach number stability achieved in ETW with second throat choked and unchoked.

Figure 6 shows Mach number against incidence for the two cases tested at a Reynolds number of 9.5 million. One is at high dynamic pressure at 300 K with the 2nd throat unchoked the other is at low dynamic pressure at 183 K with the 2nd throat choked. It illustrates that with the 2nd throat unchoked, the variation of Mach number is between 0.8464 and 0.8506.

Another problem encountered was with the transition band applied at 5% x/c. This transition band was selected for Reynolds number of 6.3 million up to 20 million. Associated with increasing the Reynolds number is a decrease in the boundary layer thickness and as a result this transition band needs to be very thin and uses a small diameter ballotini. Due to this very small ballotini size, the band is applied with cellulose dope rather than araldite (since the araldite would be thicker than the diameter of the balls) and after a prolonged period of wind on testing the band had deteriorated badly. In addition, due to the lack of 'keying' on some of the external holes filled with Cerrobend, a couple of Cerrobend plugs, became dislodged at various points during the test campaign. This highlighted the problem of a lack of model visibility in the tunnel. The model is covered by video cameras in ETW but these proved not to have sufficient coverage to replace the kind of routine model inspection available to conventional wind tunnels.

It also took considerable time to condition the balance even though the tunnel was on condition fairly quickly.

4.4 DERA 8ft tunnel test envelope

The test envelope decided upon for the 8ft tunnel was designed to confirm data obtained at ETW. Agreement of the experimental data would confirm levels measured at ETW and verify the tunnel wall corrections at high subsonic Mach numbers as these were developed at Mach numbers up to M=0.80 and had been extrapolated to the highest Mach number of this test at M=0.89. A full range of Mach numbers were tested from M=0.70 to M=0.89. The Reynolds number was the highest that could be constantly maintained across the Mach number range at $Rc=6.3x10^6$. For each wing set a standard DERA transition band was tested and also an aft band to investigate the use of the aft fixing technique to simulate increased

Reynolds number conditions. For each band a Reynolds number varies run was completed to check that transition was being tripped effectively without overfixing.

4.5 Model vibration in the DERA 8ft tunnel

Model vibration proved to be a major problems in the 8ft tests as in the earlier ETW tests. The model was lively at low lift conditions attributed to a lower surface shock wave. There was then a period where the model settled, then, as the upper surface shock developed the model became lively again causing testing to be stopped until a cure could be found. The major problems were identified on-line as pitch and roll having frequencies of 24Hz and 29Hz respectively. This resulted in the problem that once pitch was excited by shock movement, then the whole model would become excited. Unlike ETW the 8ft does not have a suitable alternative balance with a similar load range causing a change in stiffness, hence frequency. A cure was sought by using mass inside the fuselage to alter the frequencies of the model. This was possible as the 8ft-tunnel mounting was on a 75mm (3”) diameter sting whereas the ETW mounting was a 91mm (4”) diameter. Following attempts with a solid mass it was decided to shroud a cast mass in rubber allowing the mass to move. This system was tuned using modal analysis until eventually the mass was suspended inside the rear fuselage of the model on ‘o’ type ring sections of soft rubber at either end. Despite tuning of the device to the pitch frequency, modal analysis showed that the model still responded to excitation in pitch but with a marked reduction in amplitude. It is considered that the mass added damping to the system. The modification proved to be spectacularly successful considering the simplicity of the device. Tests were able to continue over the complete range of conditions.

5 Concluding remarks

At the end of the ETW test campaign, Airbus UK were asked to present a summary of the experience gained during these tests and at this presentation several recommendations were made:

- Active damping / modal analysis.
- Improve Mach stability with second throat unchoked.
- Improve video coverage of model in tunnel.
- Active balance conditioning.
- Various improvements to Variable Temperature Control Room.

All of these recommendations were acted upon by ETW and are currently being implemented / commissioned.

All of the objectives of the ATTACH 2000 research programme - Phase I were met.

- Excellent agreement between ETW and DERA 8ft tunnels. Drag to within 1 count – provides evidence that the extrapolation of the ETW wall corrections to higher Mach numbers is a valid technique.
- Due to attention to detail in design of model a high standard of build repeatability was achieved.
- High quality model.
- Repeatable transition standards.

7 References

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8 Acknowledgements

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