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THE HIGH LIFT DEVELOPMENT OF THE A320 AIRCRAFT

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ABSTRACT

The aerodynamic research and development procedures used by British Aerospace at Weybridge to design the high lift system for the new Airbus Industrie A320 airliner are described. Both the theoretical and the experimental basis are reviewed, including the use made of the large body of data on high lift devices obtained during the UK National High Lift Programme. The background to the choice and subsequent development of the A320 leading edge and trailing edge high lift devices and their optimisation on a complete three-dimensional model is discussed.

1. INTRODUCTION

This paper describes the aerodynamic research and development procedures used by British Aerospace at Weybridge to select and design the high lift system for the Airbus Industrie A320 airliner, an impression of which is shown in Figure 1.

Figure 1. The A320 Airliner

The theoretical methods used are first reviewed. In two-dimensions these range from simple inviscid surface singularity methods to fully interactive viscous solutions, while in three-dimensions a quasi three-dimensional method based on combining viscous two-dimensional theory with inviscid three-dimensional panel methods is discussed. Experimental techniques are next reviewed, with particular reference to the large two-dimensional and quasi two-dimensional models developed by British Aerospace as part of the UK National High Lift Programme. A large number of conventional and advanced high lift devices were developed using these models. Three-dimensional experimental research is also discussed, stressing the need for high Reynolds number testing, and illustrating this need with some examples.

The choice and subsequent design and development of these leading edge and trailing edge high lift devices for the A320 airliner and their optimisation in three-dimensions is discussed next. The reasons for changing the leading edge device from a rigid camber Kruger flap to a low drag over-wing slat are given, and the engineering and aerodynamic background to the decision to change the original two-element flap to a single-slotted flap is described. Finally some of the essentially three-dimensional design features such as the solution of a slat-pylon junction problem and the choice of flap track support system are discussed.

2. THEORETICAL METHODS

2.1 Two-dimensional Methods

The starting point in the design of new high lift devices is a two-dimensional theoretical study usually using surface singularity methods. Although the simpler inviscid surface singularity technique such as that due to Hess and Smith(1) still provides a surprisingly good initial design, the prediction of $C_L$max and drag is impossible without an iterative inviscid-viscous interactive theory.

At BAe Weybridge, the two-dimensional viscous theory developed in the UK by RAE is increasingly being used in the research and development of new high lift devices. This theory, known as MAVIS(2) (Multiple Aerofoil Viscous Iterative Solution) is based on the physical model shown in Figure 2, where the boundary layers and wakes interact. BAe Woodford(3) have developed an improved version of this method, with the boundary layers being represented by transpiration.

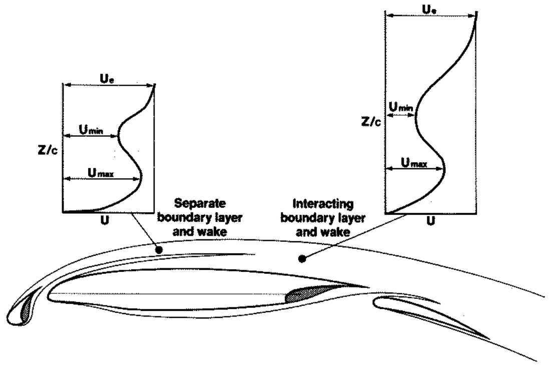

Figure 2. Viscous Theoretical Model Used in MAVIS Theory

An example of the accuracy of the method is shown in Figure 3, where the calculated pressures on a BAe designed aerofoil with slat and single-slotted flap are seen to be in good agreement with experiment, thus giving confidence in the use of the method for design purposes.

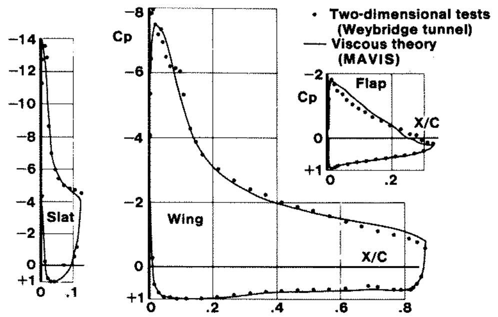

Figure 3. Viscous Theory and Experiment

2.2 Three-dimensional Methods

In extending the design process to finite wings, a three-dimensional theory is obviously necessary. For a trapezoidal wing, Woodward(4) has shown that the pressure distribution at mid-span is equivalent to that of the corresponding two-dimensional section using a simple normalisation procedure.

If the geometrical correspondence of the sections with high lift devices is such that, for

$$(x/c)_{swept} = (x/c)_{2D}$$

$$(z/c)_{swept} = (z/c)_{2D} \cos\phi_1 \qquad (1)$$

then

$$Cp_{swept} = Cp_{2D} \cos^2\phi_1 \qquad (2)$$

where ϕ_1 is the local sweep angle, and 2D refers to two-dimensional conditions.

The success of this simple procedure is demonstrated experimentally in Figure 4 using results from the UK National High Lift Programme.

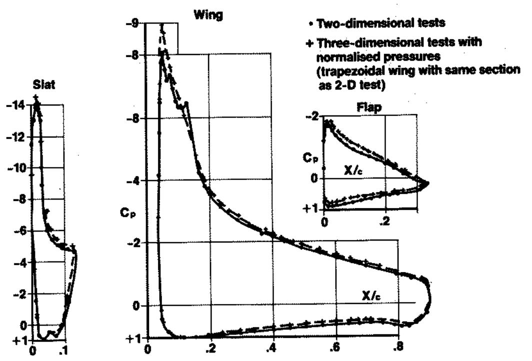

Figure 4. Comparison of Two-dimensional and Normalised Three-dimensional Pressures

This normalisation procedure leads to the possibility that the pressure distribution on a more general three-dimensional wing could be predicted by a quasi three-dimensional approach, in which the three-dimensional effects are introduced into an essentially two-dimensional calculation as an onset flow. This onset flow can be split into two components, a uniform distribution across the chord which can be obtained by normalising the geometry and pressure distributions as described above, and a non-uniform distribution which can be calculated using three-dimensional panel methods such as the BAe Hunt-Semple or SPARV panel methods.(5),(6)

The procedure is shown schematically in Figure 5, where the slat and flap slots are faired in to simplify the panel method calculations. The procedure has the great advantage that all the advances made in two-dimensional viscous theory can be utilised, while avoiding the severe complexities of a fully three-dimensional viscous multiple aerofoil approach. Calculations of this type have already been done at RAE, and suggest that for a moderate aspect ratio wing of constant section and thickness the non-uniform onset flow is relatively small over most of the span.

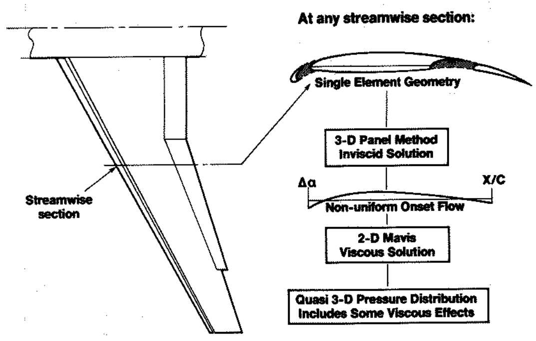

Figure 5. Quasi Three-dimensional Theoretical Method

3. TWO-DIMENSIONAL EXPERIMENTAL TECHNIQUE

Although theoretical methods are playing an increasingly important role in high lift design, wind tunnel experiment still has an essential part. The final choice and optimisation of high-lift devices and their grading across the span requires sectional testing at the highest possible Reynolds numbers.

During the 1970's the UK embarked on a major programme of high lift research called the 'National High Lift Programme' (NHLP), and as part of this, BAe Weybridge were involved in the design and testing of a wide variety of conventional and advanced high lift devices in a consistent environment. This was done by developing a large two-dimentional model and a directly related quasi two-dimensional End-Plate model, and testing at a fixed Reynolds number of 3.5 x 10^6 and a constant Mach number of 0.18.

3.1 Two-dimensional Model

A photograph of the two-dimensional model in the BAe Weybridge 4 Metre low speed wind tunnel is shown in Figure 6. The basic aerofoil section is of A300 Airbus type. To remove the substantial tunnel wall boundary layer, wall suction was employed (see Figure 7) to ensure that the flow was substantially two-dimensional. A number of basic high lift configurations were tested, and a large range of slat and flap lap and gap geometries examined, lift being measured by pressure integration and drag by wake traverse measurements downstream of the model.

In a limited number of cases total head measurements were made in the viscous layers, at several positions on the chord and this data has been useful in the development of two-dimensional theoretical methods.

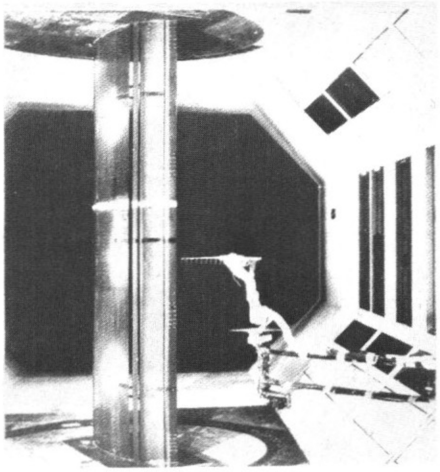

Figure 6. Two-dimensional High Lift Model in Weybridge Tunnel

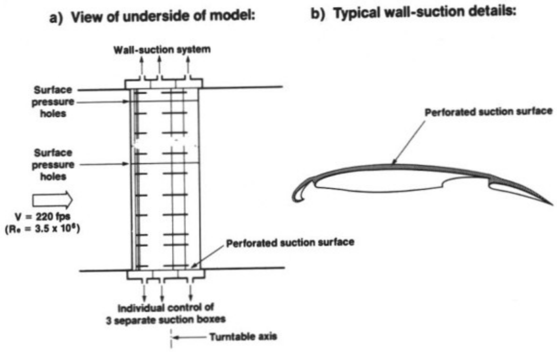

Figure 7. Two-dimensional Model with Wall Suction

3.2 Quasi Two-dimensional Model

To reduce the time and cost of testing, a quasi two-dimensional model was obtained simply by reducing the span of the two-dimensional model from 2.8m to 2.3m and fitting large end-plates. Figure 8 shows the model in the Weybridge tunnel. Pressure measurements made at pressure plotting stations at the centre-line and near one end-plate show close agreement, thus confirming that the flow over the end-plate model is essentially two-dimensional.

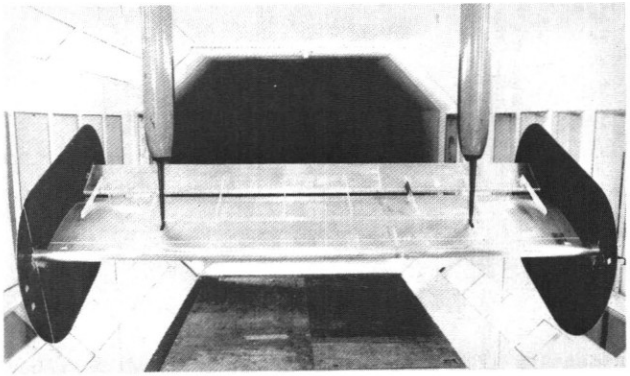

Figure 8. BAe End-plate Model in Weybridge 4 Metre Tunnel

Centre-line pressure distributions were measured on both models, and Figure 9 shows that, when compared at the same value of C_N, that is at similar values of effective incidence, the pressure distributions are very nearly the same.

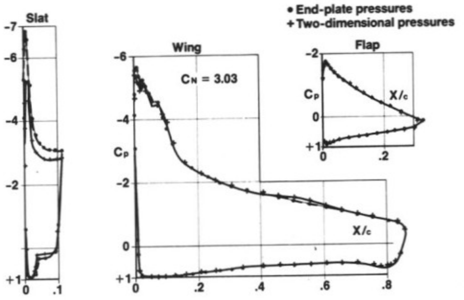

Figure 9. Centreline Pressures on Two-dimensional and End-plate Models

The down wash induced by the end-plates causes a slight increase in suction over the slat with pressures over the main wing and flap little affected. Viscous shear layer measurements were also in very good agreement when compared at the same effective incidence.

3.3 Correction of End-plate Data

The knowledge that the chordwise pressure distributions agreed so well at the same effective incidence suggested that a simple mean induced incidence correction might convert the end-plate data into essentially two-dimensional values.

$$\text{Assume } \bar{\alpha}_i = \tan^{-1} KC_L \tag{3}$$

$$\text{then } C_{L_2} = C_L(EP)\cos\bar{\alpha}_i + C_D(EP)\sin\bar{\alpha}_i \tag{4}$$

$$C_{D_2} = C_D(EP)\cos\bar{\alpha}_i - C_L(EP)\sin\bar{\alpha}_i \tag{5}$$

Where (EP) refers to forces measured on the end-plate model and suffix 2 refers to two-dimensional results or conditions.

If the value of K in equation 3 can be shown to remain constant for a number of widely different high lift configurations, then the simple correction method should work. Four widely differing high lift configurations have been tested on both two-dimensional and end-plate models (see Figure 10), including single-slotted, double and triple slotted flaps with slats and Kruger slats.

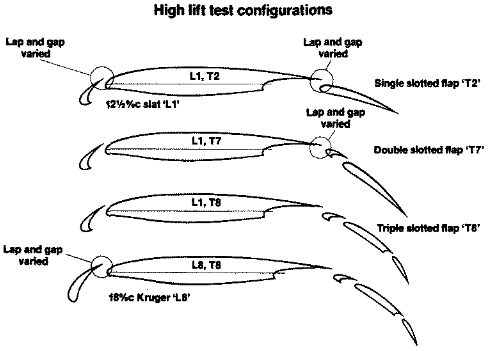

Figure 10. Two-dimensional Model High Lift Test Configurations

A single value of K was found which gave a very good collapse of the lift curves as shown in Figure 11. The corresponding drag curves were also in good agreement when an allowance was made for end-plate rig drag.

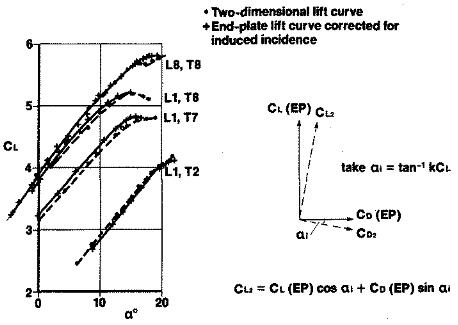

Figure 11. Comparison of Two-dimensional and Corrected End-plate Lift Curves

3.4 BAe Two-dimensional Research

As part of the UK National High Lift Programme (NHLP), BAe Weybridge designed and carried out tests, using both types of two-dimensional model, on a wide variety of conventional and advanced high lift devices, and new devices are continually being developed. A large body of data has been amassed and tested under identical conditions of fixed Reynolds number (3.5×10^6) and Mach number ($M = 0.18$).

Figures 12 and 13 give an indication of the range of leading edge and trailing edge devices tested. Besides testing a large range of deflection angles, the lap and gap geometry of most devices has been varied to establish optimum lift and drag configurations. The list includes single and double slotted flaps with different chord and shroud lengths, triple slotted flaps and

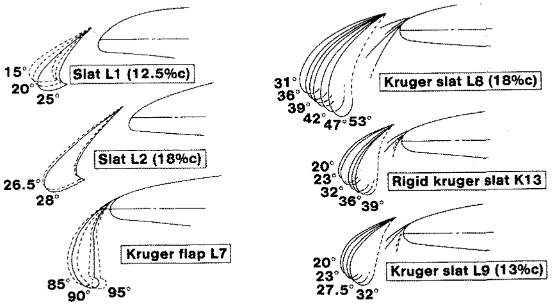

Figure 12. Leading Edge Devices Tested by BAe Weybridge (in UK NHLP)

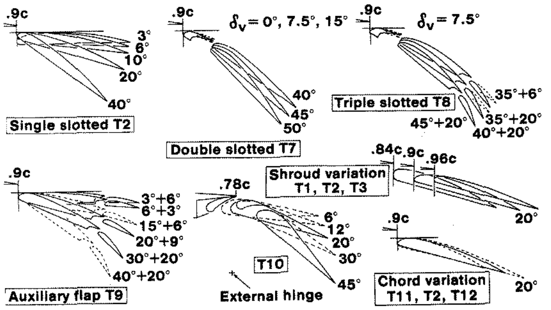

Figure 13. Trailing Edge Devices Tested by BAe Weybridge (in UK NHLP)

conventional and Kruger slats. The basic section has also been modified to represent a more advanced aerofoil section.

This data bank, to which BAe Weybridge is continually adding, provides an invaluable basis for selecting and developing advanced high lift devices for new aircraft projects.

3.5 Comparison of High Lift Devices

From the data bank referred to above, accurate comparisons of differing high lift devices can be made, and new devices evaluated for use on future projects. Also different mechanical systems proposed by the engineering design departments can be assessed aerodynamically at an early stage in the design process of a new aircraft.

A typical example of such an assessment is shown in Figure 14 where results for a conventional overwing slat are compared with those for a variable camber vented Kruger slat which retracts into the aerofoil surface. Due partly to its greater extended chord and better leading edge profile, the variable camber Kruger slat has a greater maximum lift, while its profile drag for a given value of maximum lift increment is less. These aerodynamic advantages can then be weighed against the greater mechanical complexity of the variable camber Kruger slat.

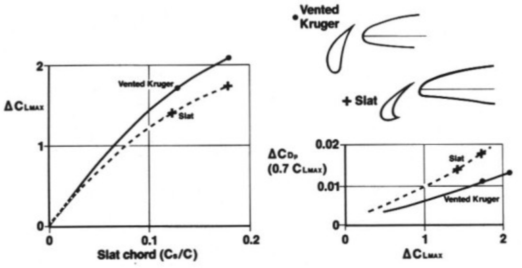

Figure 14. Comparison of Over-wing Slat and Vented Kruger

4. THREE-DIMENSIONAL EXPERIMENT

Although selection and initial design of high lift devices can be made using two-dimensional theory and experiment the final optimisation and development can only be done at present by three-dimensional testing at high Reynolds number on the actual aircraft geometry. In spite of the current advances in theoretical methods, the task of designing and developing devices completely theoretically on finite wings is still not possible due to the complexity of the flows involved, particularly at the stall.

4.1 High Reynolds Number Testing

Although initial three-dimensional development is usually done at the lower Reynolds number of a large atmospheric tunnel such as the Weybridge 4m tunnel, BAe is now making considerable use of the much higher Reynolds numbers which can be obtained in the RAE 5m tunnel which can be pressurised to 3 bars.

The necessity for testing at high Reynolds number can be illustrated by some of the development work on an early interim A320 model. This model is shown in Figure 15 in the Weybridge 4m tunnel and in Figure 16 in the RAE 5m tunnel. Although of A320 planform the wing sections are not of A320 design.

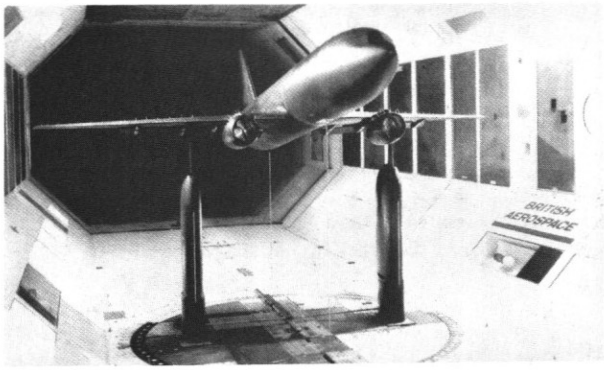

Figure 15. Early A320 Model in Weybridge 4 Metre Tunnel

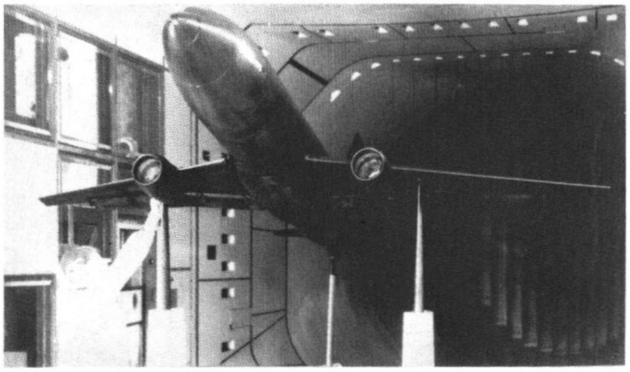

Figure 16. Early A320 Model in the RAE 5 Metre Tunnel

Figure 17 shows that, when the slat lap and gap geometry was varied at the high Reynolds number the position for maximum $C_L$max was different from the obtained at the low Reynolds number although the $C_L$max contours are broadly similar in character. The corresponding drag contours shown in Figure 18 are however very different at the different Reynolds numbers, only the high Reynolds number drag optimisation showing a clearly defined minimum drag position some distance from the fixed leading edge profile. It is also interesting to note that the maximum $C_L$max and minimum drag positions are significantly different.

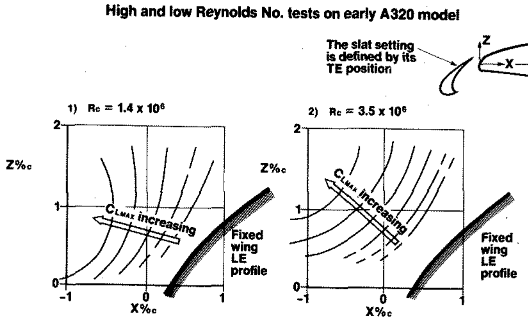

Figure 17. $C_L$max Contours for Movement of Take-off Slat (δ_s = 20°)

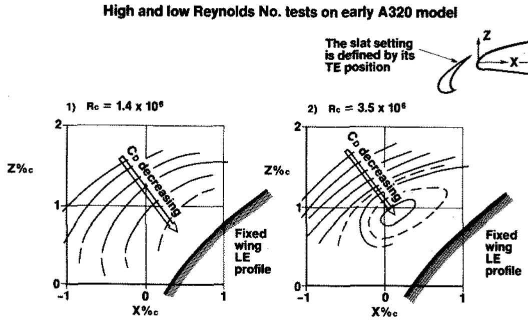

Figure 18. Drag Contours for Movement of Take-off Slat (δ_s = 20°)

4.2 Slat and Flap Track Development Model

Theory is of little use in the development of the detailed design of the tracks which attach the slats and flaps to the main wing. To obtain high Reynolds numbers, and the physical scale necessary to represent the complex mechanical track systems, BAe Weybridge have developed a large swept end-plate model for studying the detailed aerodynamics of flap tracks, flap track fairings and slat tracks.

The model is shown in Figure 19; lift and drag forces are measured on the balance, and good correlation with flight test results has been achieved with this model.

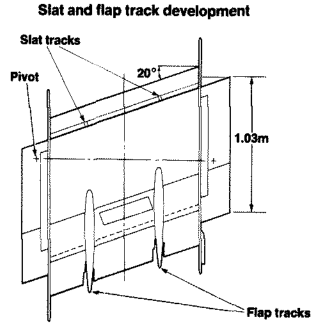

Figure 19. Weybridge Swept End-plate Model

4.3 High Reynolds Number Research Models

To exploit longer term the high Reynolds numbers of the RAE 5m tunnel, BAe is designing and manufacturing two high lift research models for high Reynolds number work in this tunnel. The first model, AGC-1 is a large half-model, giving a Reynolds number of about 10×10^6 and extensively equipped with pressure tappings and boundary layer rakes for fundamental research. The other model AGC-2 is a complete model, also with pressure tappings, for more general high lift research; it can also be fitted with turbine-powered simulators to represent engine power effects.

5. A320 HIGH LIFT DESIGN

Prior to the official go-ahead for the A320 in 1984 an Airbus Industrie team known as the Integrated Wing Group was set up at Weybridge in 1981 to agree on the basic design of the wing. The group consisted of engineers from the partner companies in Airbus Industrie, BAe, MBB and Aerospatiale. In 1982 the BAe Weybridge high speed wing design was chosen for the A320, one of its significant advantages from the low speed point of view being its deep rear spar and section.

With its background of theoretical methods, an extensive experimental data base, and the experience gained on the existing A300 and A310 aircraft, BAe was in a very good position to take on the main responsibility for designing the A320 high lift system, a task which it now shares with MBB.

The basic high lift configuration defined by 1984 is shown in Figure 20, the wing, of 9.4 aspect ratio and 25 degrees sweep, has a nearly full span leading edge slat and a continuous span single-slotted trailing edge flap, and the background to the choice and subsequent development of both leading edge and trailing edge devices and their optimisation is discussed next.

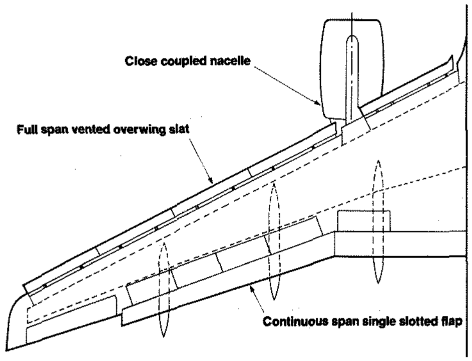

Figure 20. A320 High Lift System

5.1 A320 Leading Edge Devices

During the early initial design stage of the A320, BAe proposed a rigid camber Kruger flap as a leading edge device, as it showed promising aerodynamic and engineering advantages over a conventional slat. The rigid Kruger flap which did not form a slot when deployed is shown in Figure 21. It was light, and had low drag at take-off, which was a basic requirement for the A320. However its maximum lift at landing was inadequate.

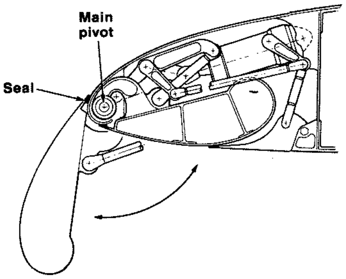

Figure 21. Rigid Camber Sealed Kruger Slat

The NHLP work had suggested that there might be a low drag position for an over-wing vented slat at the take-off angle, and further testing, see Figure 22, confirmed this. The maximum lift at landing obtained by extending the vented slat on its simple circular arc track now proved to be entirely adequate.

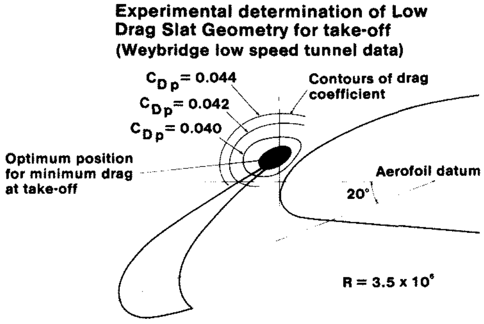

Figure 22. Low Drag Slat Optimisation

5.2 A320 Trailing Edge Devices

The Integrated Wing Group considered a number of different trailing edge flap systems for the A320, and initially a two element flap designed by BAe Weybridge was selected. This flap and an indication of its track system is shown in Figure 23. The second slot was sealed for take-off giving low drag, and vented for landing giving a high maximum lift. The main flap rotated through only 25 degrees giving a small and hence light flap track system.

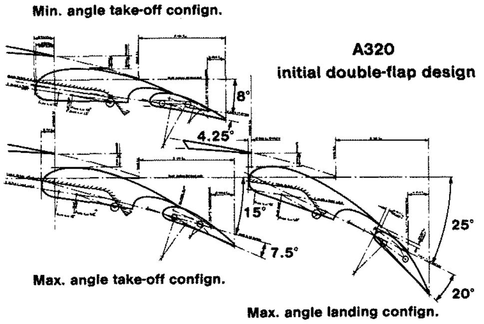

Figure 23. Geometry of Double-flap

However, the relatively deep rear section of the A320 had allowed the flap to have a generous nose radius, which, as Figure 24 shows, results in a much reduced peak suction and hence a higher $C_L$max compared with the more conventional NHLP flap. Further testing showed that the second slot of the initial double-flap design could be eliminated without significant loss of maximum lift for landing. This resulted in a nett weight saving and the flap system finally designed for the A320 is shown in Figure 25.

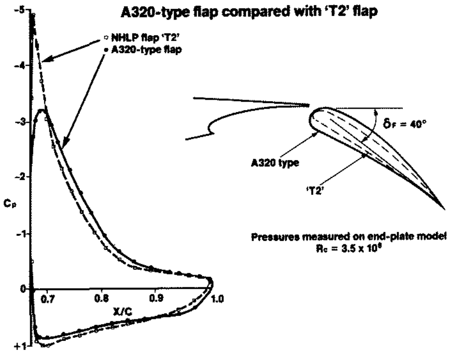

Figure 24. Pressure Distributions on Landing Flaps

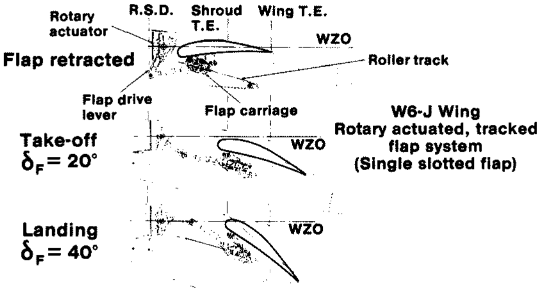

Figure 25. Single-slotted Flap System

5.3 Three-dimensional Design

The leading edge and trailing edge devices selected were then fitted to a representative A320 complete model which has been extensively tested in the BAe Weybridge 4m tunnel (see Figure 26). It has also been tested in the RAE 5m tunnel (Figure 27), where the essential final checks on optimum lap and gap geometry and any spanwise variation can be carried out at the highest possible Reynolds number.

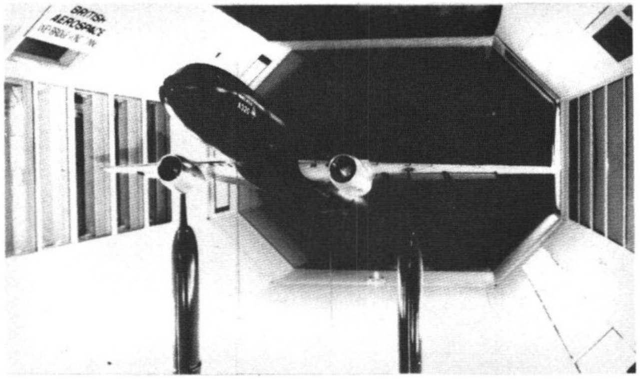

Figure 26. A320 Model in Weybridge Tunnel

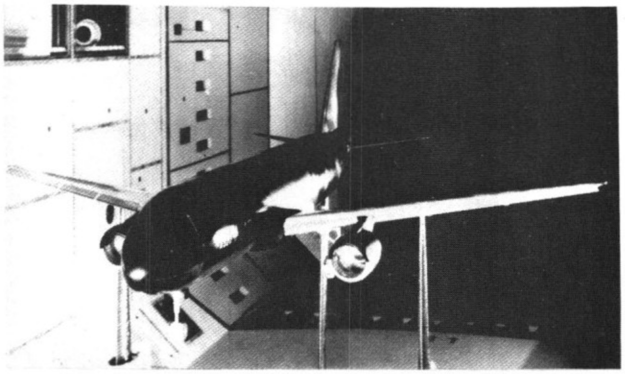

Figure 27. A320 Model in the RAE 5 Metre Tunnel

One of the differences between the A320 and the A310 is that the engine nacelle is relatively closer to the wing, with the result that the nacelle pylon divides the leading edge slat into two separate spanwise segments as shown in Figure 28. This more closely coupled nacelle installation initially resulted in a loss of maximum lift, but, as shown in Figure 29, this loss has been almost entirely recovered by modifications developed in the Weybridge 4m tunnel and confirmed in the RAE 5m tunnel.

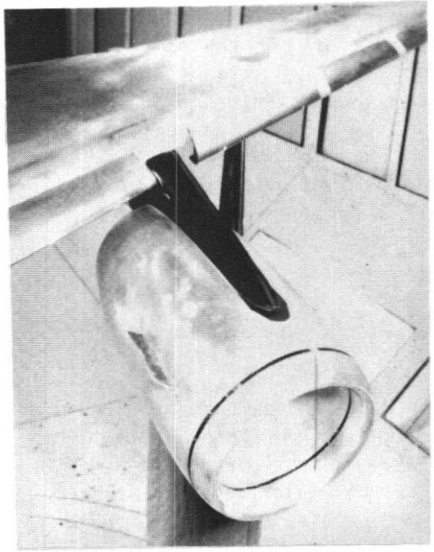

Figure 28. A320 Slat Pylon Intersection

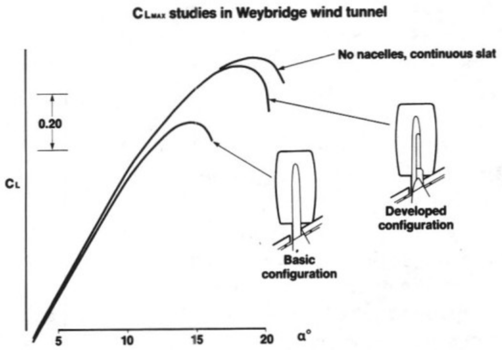

Figure 29. Slat/Pylon Junction Development

5.4 Flap Track Systems

Different flap track systems were studied by the Integrated Wing Group, and although an end-supported system was chosen originally, further engineering work showed that for a number of reasons, an underslung beam system was a better choice for the A320. The Weybridge track development model referred to earlier was used to check the aerodynamic implications of this choice, and the comparison given in Figure 30 shows the underslung beam system to be marginally superior in terms of higher $C_L$max and lower profile drag.

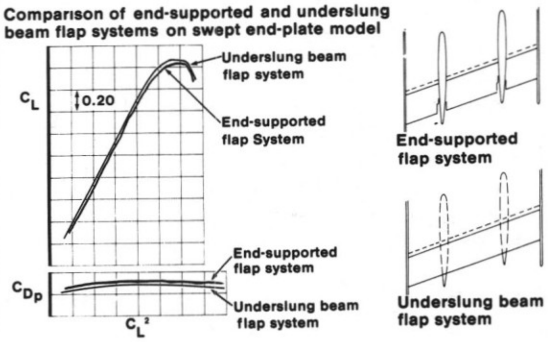

Figure 30. Comparison of Flap Support Systems

5.5 Engine Jet Simulation

An important part of the low speed development of a new aircraft is the installation effect of the nacelle-engine combination, particularly the effect on climb lift-drag ratio. MBB, who have the responsibility for this aspect of the A320, have developed turbine powered simulator (TPS) installations to investigate jet effects at low speed on the A320.

6. CONCLUSIONS

The first part of this paper describes the research and development process used by BAe Weybridge to design efficient high lift systems, ranging through two-dimensional inviscid-viscous theory, two-dimensional experiment including use of the large data base of the UK National High Lift Programme, to three-dimensional experiment on complete aircraft models. The importance of testing at high Reynolds number is stressed.

The second part shows how the A320 high lift system was designed and developed using this process, and how the engineering and aerodynamic requirements interacted.

The high lift system designed for the A320 has a simple, but efficient near full span leading edge over-wing slat, and a trailing edge flap system which is continuous across its wide span (including behind the engines) and consists of only two spanwise segments. This, together with the single-slotted flap section, combines physical simplicity (and hence lightness and low cost) with excellent aerodynamic characteristics. The high lift system now being embodied in the A320 meets the stringent requirements of high lift-drag ratio together with high maximum lift for take-off, and a high maximum lift coefficient in excess of three for landing.

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