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REDUCTION OF WAVE AND LIFT-DEPENDENT DRAG FOR SUPERSONIC TRANSPORT AIRCRAFT

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[This paper is based on work by many members of the EUROSUP consortium, including T Surply and D Prat (Aerospatiale), M Averardo (Alenia), S Rolston and K Nicholls (British Aerospace Airbus), A Vicini (CIRA), U Herrman (DLR), A Elsenaar and J van Muijden (NLR), D Destarac, P Lemee and R Grenon (ONERA), E Totland (Saab), and J Doherty and T Evans (DERA).]

Abstract

Research funded by the European Commission to reduce the drag of supersonic transport aircraft at low speed and cruise (transonic and supersonic), and to assess relevant aerodynamic design methods, is described. The EUROSUP project, co-ordinated by the UK Defence Evaluation and Research Agency, has ten partners contributing computational and experimental work. Results are presented for the first two stages of the research. Firstly the evaluation of computational fluid dynamics methods against wind-tunnel data for a supersonic transport aircraft configuration is described. Secondly results are presented for two linked wing-design tasks: dual-point transonic / supersonic cruise design (using linear, inverse and optimisation methods with geometric and aerodynamic constraints) and low-speed design. Three configurations of the wing resulting from this triple-point design are to be tested in 1998 to assess the aerodynamic design. Optimised deflection of segmented leading- and trailing-edge flaps at the transonic design point is predicted to produce excellent L/D performance without compromising the supersonic performance. Estimates of L/D performance at low speed indicate that the target value can also be achieved by using optimised deflections of segmented leading-edge flaps, but major limitations were exposed in current computational methods for low speed design. Further research is recommended in this area.

Introduction

With the experience gained in the design and operation of first-generation supersonic transport aircraft, Europe has a firm base on which to consider improved design methods and the technologies for a second-generation aircraft. Surveys of the demand for such an aircraft have shown that a substantial market exists if the fare levels can be maintained close to those for subsonic transport aircraft, by the application of advanced technology. Considerable improvements are required in materials, structures, aerodynamics, propulsion (including emissions), and aircraft systems. In aerodynamics, significant advances are necessary in wing design, propulsion-system installation and configuration integration. To meet some of these needs the European Commission has funded the EUROSUP project to address the following objectives:

- the reduction of aircraft drag at low speed, including take-off and landing conditions, to minimise the engine thrust required and hence the noise and emissions generated by the aircraft
- the reduction of aircraft drag at cruise conditions over land (transonic) and over sea (supersonic), to reduce the fuel required and hence increase the payload and cost effectiveness of the aircraft.

From these requirements three targets for aerodynamic performance to produce a viable second generation supersonic transport aircraft were defined:

- lift/drag ~ 10 at supersonic cruise ($M = 2.0$)
- lift/drag ~ 15 at transonic speeds ($M = 0.95$)
- lift/drag ~ 8 at low speed ($M \sim 0.3$)

These targets for aerodynamic performance represent an improvement of between 20% and 30% relative to that achieved for the first generation of supersonic transport aircraft.

An objective of equal importance to industry is the need for an aerodynamic design method that allows rapid completion of a design cycle. A design cycle consists of the optimisation of the geometric shape to maximise aerodynamic performance, subject to packaging and off-design performance constraints, followed by mission performance analysis, and includes the consideration of the corresponding changes in the aircraft structure and propulsion system. Within the EUROSUP project the relative merits of alternative aerodynamic shape design methods with respect to speed of execution, ease of use and the ability to incorporate updates to design constraints are being assessed.

The three-year project which started in January 1996 is funded 50% by the Commission of the European Union and has ten industrial and research establishment partners. The consortium consists of airframe

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companies from France (Aerospatiale), Germany (DASA), Italy (Alenia), Sweden (Saab) and UK (British Aerospace Airbus), and research establishments from France (ONERA), Germany (DLR), Italy (CIRA), the Netherlands (NLR) and UK (DERA). The UK Defence Evaluation and Research Agency is co-ordinating the project. An overview of the research programme is given in the next section. This is followed by sections describing the research tasks completed up to April 1998: computational fluid dynamics (CFD) method evaluation, and wing design for supersonic, transonic and low-speed conditions. Conclusions drawn from the work completed and future work plans are summarised.

Research Programme

To achieve the objectives stated above a programme of computational and experimental research is being followed. Figure 1 shows the broad breakdown of the research activities among the EUROSUP partners. Each task has a leader and several contributors drawn from the consortium.

Several CFD methods, covering a range of fidelity in flow modelling, were first evaluated for their accuracy and speed of prediction against an existing set of wind-tunnel data for a generic configuration for a supersonic transport aircraft. The outcome of this work has fed into the analysis work in subsequent tasks. Two linked wing-design tasks have been completed in parallel; one task for the transonic/supersonic cruise design and the other for low-speed high-lift design. Several CFD-based methods have been used for these tasks, again covering a range of speed and accuracy of flow modelling. The results of these design tasks have been used to define three configurations of a single wing shape for a wind-tunnel model. Design and manufacture of the model is due to be completed in May 1998, for testing at low-speed, transonic and supersonic conditions.

The experimental data from the wind-tunnel tests will be analysed to assess the design methods and to compare the measured aerodynamic performance against the levels predicted by CFD and the initial aerodynamic targets for L/D. This process will reveal any shortcomings in the existing aerodynamic analysis and design tools, and identify further needs for technology development. The results of the research will be exploited by the industry partners in the EUROSUP consortium in future feasibility studies for supersonic transport aircraft. The findings on CFD and design method capabilities can be expected to have more general exploitation for combat aircraft and subsonic transport aircraft.

Figure 2 shows the interrelation of these research tasks and the overall timescale for the work.

CFD Method Evaluation

Purpose

The chief aim was to assess the relative suitability of established CFD codes based on four flow models in a supersonic transport application. These codes form the basic tools for the subsequent design and analysis tasks. Drag reduction being the main focus of the overall project, emphasis was placed on drag prediction accuracy.

Another purpose was to investigate, for supersonic flow, the aerodynamic effects of perturbations in wing section camber, spanwise twist distribution, outer sweep angle, and wing/fuselage location, in order to provide guidance for the wing design work. This was done through the application of linearised theory and the area rule concept, by Alenia.

Approach

The basis for the CFD method evaluation was an experimental database provided by Aerospatiale. This consisted of results from force and pressure measurements on an Aerospatiale ATSF-1 model (fig 3), tested at supersonic, transonic and subsonic conditions in the ONERA S2MA wind tunnel. The codes involved in this evaluation task covered a wide range of physical models:

- Alenia and CIRA used a method based on the linear theory and area rule for computing lift-dependent and wave drag, and simple flat-plate formulae for skin-friction drag.
- Euler computations (inviscid, non linear) were carried out by CIRA, NLR and ONERA. Fig 4 shows the surface mesh used by ONERA and CIRA. The effect of grid refinement on pressure drag (inviscid) obtained by solving the Euler equations was investigated by NLR. This study was required because of the necessity to use coarse grids for the optimisation methods employed for wing design.
- ONERA also performed viscous boundary layer computations using the surface velocity field from the Euler computations (without coupling), thus complementing the pressure drag results with skin-friction drag.
- DLR used a Navier-Stokes solver (with an algebraic turbulence model), which offered the most complex and theoretically adequate physical model (non-linear, viscous). Fig 5 shows the surface mesh used by DLR.

Results

The computations by CIRA[(1)] showed that in supersonic flow linear theory methods, although unable to predict pressure distributions accurately, offered accuracy of prediction of overall coefficient values almost as good as those from Euler codes, provided that the wing has sharp leading-edges so there is no significant leading-edge suction peak. In subsonic and transonic flow the CIRA Euler code was able to capture the essential flow features typical of these regimes, including primary vortex development at low speeds and high angles of attack. The study of grid refinement effects on Euler solutions by NLR[(2)] showed that in supersonic flow a coarse grid (100,000 points) is capable of resolving the inviscid flow with acceptable accuracy for values of overall forces and pitching moment. In transonic flow coarse grids clearly cannot ensure such accuracy, and refinements over one million points may be necessary.

The Euler field solution + boundary layer approach of ONERA[(3)] combines the ability of an Euler code to predict the essential features of supersonic, transonic and subsonic flows, with the capacity of a boundary layer method to provide the skin-friction drag component. However, the boundary layer approach is not applicable to separated flow cases at low speed and high angle of attack.

The computations by DLR[(4)] indicated that Navier-Stokes codes are promising tools for flow analysis. However poor prediction of separated subsonic flows was obtained. This may be ascribed to limitations in the turbulence modelling used, the algebraic Baldwin-Lomax turbulence model, without the Degani-Schiff correction which allows the model to differentiate between the vorticity within the attached boundary layer and the vorticity on the surfaces of separation. As with the Euler model it was found that accurate flow prediction required finer grids in transonic flow than in supersonic flow.

An overall comparison by ONERA[(5)] of the computational and experimental results showed improved levels of agreement as the Mach number increased from the subsonic to transonic regime to supersonic regimes. This applied for the pressure distributions as well as for the values of overall force and moment coefficients.

At M = 2 the scatter of the computed values for inviscid drag was about 10 drag counts (fig 6). After taking account of skin friction the experimentally measured drag lies within this range. Small differences in the predictions for inviscid drag by linear and non-linear methods appeared at high C_L where the non-linear phenomena become stronger. Skin-friction drag computed by solving the Navier-Stokes equations is higher than that given by boundary layer computations and flat plate formulae (fig 7).

At M = 0.95 the scatter of the computed values of drag coefficient increases from 20 drag counts at low C_L to 35 counts at high C_L. Again the measured drag lay within these boundaries, with the Navier-Stokes results overestimating it, and the Euler + boundary layer underestimating it. These discrepancies came largely from errors in the friction drag evaluation, but with some contribution from the pressure drag. Note that the viscous pressure-drag component is not taken into account in the Euler + boundary layer computations.

At M = 0.25, a separated flow case, neither the Euler + boundary layer nor the Navier-Stokes calculations (with Baldwin-Lomax turbulence model) were able to give reliable drag prediction. The main features of the flow were captured by the Euler codes.

In predicting the lift for sub-, trans- and supersonic flow cases all the methods (except Navier-Stokes in subsonic flow) required a lower angle of attack than in experiment to produce a given C_L. The computed values of C_m were lower than the measured values for all flow regimes.

In general the computed pressure distributions using the Euler or Navier-Stokes codes showed excellent agreement with the experimentally measured values in supersonic flow. Some discrepancies appeared in transonic flow as a lack of resolution of the suction peaks and shocks, and an inability to predict the onset of vortical flow. In subsonic flow the Euler codes predicted primary vortices similar to those measured in experiment, but the secondary separation could not be predicted. The quality of the Navier-Stokes results (in subsonic flow) was impaired by the use of an unsuitable turbulence model. There was evidence to suggest that the numerical dissipation inherent in some of the flow solvers (viscous as well as inviscid) may be responsible for some of the errors in predicting the flow physics.

Conclusions

On the basis of these computations, for supersonic design it was concluded that linear methods are adequate for the initial design phases. They offer acceptable prediction accuracy for drag and lift, while their high computational efficiency permits the analysis of a much larger number of configurations than Euler and Navier-Stokes codes. It was also concluded that supersonic and two-point supersonic / transonic design could be carried out with optimisation methods based on Euler solutions on less fine grids.

The use of medium to coarse grids in three-dimensional shape optimisation, for reasons of cost and speed, is entirely justified in supersonic flow. Grid requirements for accurate aerodynamic performance prediction are more severe in transonic flow. The reliability of computations on a coarse grid in the optimisation process becomes questionable. Thus it is essential to use high density grids for the analysis by Euler codes of optimised shapes obtained at transonic and transonic / supersonic dual-point conditions.

Computations using Navier-Stokes flow analysis codes are essential to complement Euler calculations as viscous effects are unlikely to be negligible in transonic flow. At low speed, fine-grid Euler computations were able to reproduce a believable model of leading-edge separation. However the present study did not cover the assessment of separation prediction or the drag analysis of separated flows. Reliable Navier-Stokes computations for these conditions are likely to require more sophisticated turbulence modelling than the simple algebraic models used in the work reported here.

Effect of changes in wing parameter values

The main results from the study of drag sensitivity to shape changes carried out by Alenia(6) were:

- optimisation of the inner wing has the greatest effect on supersonic L/D
- the lift-induced drag is very sensitive to the shape of the inboard wing sections; reduced incidence of the airfoil at the wing-fuselage junction increases aerodynamic efficiency (L/D)
- wave drag, being related to the global volume and the longitudinal distribution of cross-sectional area, can be affected by the longitudinal shifting of the wing along the fuselage, or by a change of the outer wing sweep, but not by camber or twist modifications
- promising configurations are characterised by a low wing-body angle and / or section camber, which thus have a small negative impact on the lift performance but give high aerodynamic efficiency.

Problems encountered

For the Navier-Stokes calculations there were problems in generating the surface grid in the region of the leading edge on the inboard part of the wing. These were found to be due to the high local surface curvature. For the Euler calculations the handling of the CATIA data was more time-consuming than expected and the grid generation complicated by the presence of a vertical tail. To minimise these types of problem in the CFD analysis tasks associated with the wing design, the use of a CAD description was avoided by providing surface grids. The design problem was simplified by omitting the vertical tail.

Transonic/Supersonic wing design

Purpose

This was the prime activity of the EUROSUP project. Previous European design of supersonic transport aircraft (i.e. Concorde) was based on supersonic linear theory supported by extensive testing of wind-tunnel models to refine the wing shape. The aim of the EUROSUP research has been to demonstrate that new design methods based on the use of CFD codes in combination with numerical optimisation techniques can define wing shapes having significantly higher values of L/D than those achievable with linear theory methods, while considering multiple design points (low-speed and transonic cruise in addition to supersonic cruise). Because of the strong interaction between low-speed and high-speed design (for example the degree of bluntness employed on the wing leading edge) it has been essential to maintain close co-ordination of these tasks in the project.

Approach

Configuration The European Supersonic Civil Transport (ESCT) configuration(7) formed the basis for the aerodynamic design. The geometry of this research configuration is shown in figure 8. To meet the requirements for manufacture of a wind tunnel model the fuselage was simplified to have a circular cross section, however the cambered nose and fuselage cross-sectional area distribution were not modified. This fuselage geometry and the wing planform remained fixed throughout the design work. The untwisted, uncambered wing was used as the datum against which the performance of the new wing designs was assessed.

Design variables were the wing twist, camber and thickness distributions, and the overall configuration incidence at each design point.

Design constraints were defined(7) to ensure geometric layout and aerodynamic requirements were satisfied. Minimum values were defined for the depth of the undercarriage bay, for the front and rear spar depths, and the wing section maximum thickness at 5 spanwise stations. The upper surface of the wing was constrained to be below the cabin floor over the entire cabin area and the lower surface of the wing was constrained not to protrude below the bottom of the fuselage. Figure 9 shows the geometric constraints imposed. The overall lift coefficient was constrained to the value required at the design point under consideration. For the later stages of design(11) constraints were also imposed on the maximum value of local Mach number on the front and rear portions of the upper surface of the wing. This was found necessary to prevent the optimisation process producing wing shapes with unacceptably high adverse pressure gradients in inviscid flow.

Design methods Four methods were used for aerodynamic design with the common aim of minimising drag at the high-speed design points.

- Alenia used linear theory for manual design(8) at the supersonic design point, and an Euler method for analysis at the transonic design point.
- ONERA(9) and DERA(10) used optimisation methods based on Euler flow solutions for single and dual-point design at the transonic and supersonic design points.
- SAAB used an inverse design method based on an Euler flow solver.

The linear theory method is fast but gives less accurate physical modelling, so it was used for initial design to provide a starting geometry for the other methods. The direct optimisation methods provide very flexible design capabilities but require large computation times. The inverse method was used to investigate details of the wing shapes produced by the other partners through the appropriate choice of target pressure distributions.

Results

Alenia completed a single-point optimisation at the supersonic design point, for which the wing thickness distribution was fixed to satisfy the geometric constraints. Wing twist and camber were varied to optimise L/D performance. The Alenia design(8) exceeded the transonic L/D target and came within 4% of the supersonic target, illustrating the effectiveness of linear methods for design (figure 10). To achieve this result Alenia used thickness distributions for the wing sections that had a sharp leading edge, which is likely to limit the potential performance of the wing at low speed.

ONERA then completed a single-point optimisation at the supersonic design point, using an Euler CFD code, in two stages. The wing thickness distribution was first optimised for an untwisted and uncambered wing. This thickness distribution was then used in an optimisation of wing twist and camber. The resulting wing shape produced improvements in L/D of 1% transonically and 0.5% supersonically, relative to the Alenia design, but it featured a round leading-edge shape which would be likely to give improved low speed performance. Figure 11 illustrates the improvements obtained at the supersonic design point. The combination of thickness, camber and twist design results in a large reduction in the strength of the leading-edge shock.

DERA made some minor refinements to the ONERA single-point supersonic design, by further optimisation of the thickness and twist of the wing. This produced a small improvement in supersonic L/D. The bulk of the DERA work(11) concerned the transonic design. An important prerequisite for this work was an ability to resolve the wing flow features on a grid coarse enough for design by optimisation. The comparison in figure 12 of pressure distributions computed with fine (486000 cells) and coarse (85000 cells) grids shows this could be achieved with the DERA CFD code SAUNA(12). A single-point transonic design was completed using the modified ONERA supersonic design as a starting point. The thickness distribution was retained unchanged and the wing twist and camber optimised. The resulting design exceeded the transonic L/D target by a wide margin, but was 10% below the target value for supersonic L/D. In addition the upper surface pressure distribution had a high suction peak at the leading edge and a relatively strong trailing edge shock, both features likely to cause flow separation and hence additional drag, leading to further reductions in L/D. Shape optimisation with constraints imposed on the magnitude of these peaks reduced the transonic L/D significantly. It was concluded that a fixed geometry could not meet all the design objectives. The basic wing shape was therefore frozen as the single-point supersonic design and the remainder of the DERA work focused on defining the optimum deflection angles for segmented leading- and trailing-edge flaps to maximise transonic L/D, with the constraints on upper surface pressure included. Fig 13 shows the coarse grid used for wing design with deflected leading-edge flaps.

Conclusions

The geometries obtained from the aerodynamic design work at Alenia, ONERA and DERA all met the basic geometric and aerodynamic constraints(7). Figure 14 shows the relative L/D performance of the resulting wing shapes at the transonic and supersonic design points. The Alenia linear-method design (B) achieves almost as large an improvement in the supersonic L/D over the datum wing (A) as the ONERA and DERA single-point supersonic designs (C) and (D1) using Euler-based methods. As noted above the Alenia design has a sharper leading-edge profile than the other designs and is thus probably inferior for low-speed L/D performance. Figure 14 shows that a large increase in transonic performance is achievable (D1 to D2) by using variable geometry (segmented leading- and trailing-edge flaps). From design E in figure 14, a dual-point transonic / supersonic design, also with variable geometry used at the transonic design point, it can be seen that there is no benefit from this approach. The results of the EUROSUP design work show that the use of variable geometry minimises any interaction in the achievement of transonic and supersonic L/D targets. The results achieved are a considerable advance over those from previous dual-point design work with fixed geometry, for example at DERA(10).

The aerodynamic design work has shown that the transonic / supersonic design problem was closely constrained. The scope for geometric shape modification was restricted very considerably by the spar depth, undercarriage bay depth and cabin floor constraints. This in turn limited the potential for improvements in aerodynamic performance relative to the datum. By the same token the design problem has been a challenging test for the shape optimisation methods employed.

The two wing configurations, one for the supersonic design point and the other, with graduated deflections of a leading- and trailing-edge flaps, for the transonic design point are being analysed by NLR, CIRA, and DLR using their CFD methods.

Low-speed aerodynamic design

Purpose

The aim of the EUROSUP low speed design task was to use variable leading-edge geometry to reduce drag in order to meet the airport noise limits. The aerodynamic efficiency of the aircraft in terms of L/D is believed to be most critical at the flyover noise point. Hence the flyover flight condition of $C_L = 0.4$ was chosen as the design condition. Trailing-edge devices were not investigated due to the potential trimming problems. It was essential that the low speed design should not compromise unduly the high-speed performance.

Approach

Two alternative approaches have been examined to achieve the L/D target. BAe and DERA have investigated hinged leading-edge devices and Alenia have examined slotted leading-edge devices. DERA used the CODAS Euler optimisation method to assist in the design of the configuration of the leading-edge flaps that were selected for model testing. The ESCT geometry and design criteria were used for the low speed design work. Initial work was done with the untwisted, uncambered datum wing and the final optimised design of the leading-edge devices was performed on the wing resulting from the high-speed design work.

Slotted Devices

Alenia have completed a 2D and a 3D analysis of a leading-edge slotted device. The slat cut line was based on experience with subsonic transport aircraft and an external fixed centre of rotation was used.

2D analysis A 2D viscous / inviscid interaction method that incorporates a 1st order panel method and semi-inverse coupling was used on an ESCT wing section, for the clean and slatted wing configurations for several slat deflection angles. The results showed that the stall arose from flow separation on the slat and that the maximum increment in C_{Lmax} was achieved with the slat deflected 16°. The optimum slat angle varied with C_L such that at low C_L, the clean configuration gave the highest L/D, whereas at high C_L a slat angle of 16° was optimum.

3D analysis was performed on the ESCT datum wing without a fuselage. The 2D slatted wing section was scaled and a constant slat deflection was assumed across the span. Thin layer Navier-Stokes calculations were performed for the clean wing and the wing plus slat configurations using the ENFLOW code. The results indicated that slat deflection delayed flow separation in the outboard region and hence a large L/D increase was achieved at high incidence.

Hinged Devices

Datum values for the deflection angles of the hinged leading-edge flap segments were defined by BAe using a manual design method based on extensive low-speed wind tunnel results. RANSMB Navier-Stokes calculations were then performed by BAe on this configuration, initially with a 2-equation k-g turbulence model and 1.76 million cells. A single flow solution was obtained using a Baldwin-Lomax model and the results showed that considerable differences existed between solutions with the two turbulence models. The results indicated that the datum leading-edge deflections improved L/D at the design condition by 11% and the design target could be achieved.

In preparation for use of the CODAS design method to optimise the leading-edge configuration, DERA completed flow analyses with the SAUNA Euler code on coarse and fine grids for a representative angle of incidence. Noticeably different solutions were obtained for the two grids, and comparisons with results from the BAe Navier-Stokes computations also showed large differences in the predicted pressure distributions. A possible explanation is that the flow over the datum geometry is unsteady for the cases analysed.

CODAS was used by DERA to design a leading-edge deflection on the datum wing with the objective of identifying the peak suction and minimising it. The code significantly altered the deflections compared to the datum and the peak suction was reduced by 45%. However, analysis of the resulting configuration using the BAe RANSMB code predicted a reduction in L/D relative to that of the datum leading-edge configuration.

The final supersonic wing geometry then became available and attempts were made to optimise the leading-edge deflections using alternative design objectives. The low speed flow over the new wing was seen to be significantly different from that predicted for the datum wing. Some progress has been made with this optimisation but the results have not been adequately validated. Figure 15 summarises the work on the hinged devices. It can be seen that results from the manual design method and the Navier-Stokes computations indicate that the target value of L/D can be achieved at $C_L = 0.4$.

Conclusions

The Navier-Stokes results showed significant areas of separated flow with the leading-edge deflected and this has raised doubts about the validity of the flow solutions obtained at the low-speed design condition. Inaccuracies in the Euler flow solutions due to poor convergence etc, combined with the need to use a coarse grid for the CODAS application, prevented a useful outcome from the optimisation design approach. There was no computational means of determining the level of suction for the onset of separation. The mechanism for the drag reduction evident in previous wind-tunnel tests was not fully understood and could not be modelled computationally. Further evaluation of the CFD methods is required for this class of flow.

From this work leading-edge flap deflection angles for the 5 flap segments were chosen for the wind tunnel model, and the geometry was supplied to NLR for model design and manufacture.

The low-speed wing configuration is being analysed by DLR using the CFD method previously evaluated in the project. Figure 16 shows results from a typical Navier-Stokes computation for a configuration without leading-edge device deflection and illustrates the complexity of the flow about a cranked arrow planform.

Experimental validation

A sting-mounted model (1/80 scale of ESCT) consisting of a fuselage with a cylindrical afterbody and three wings has been designed and is being manufactured by NLR. The three wing configurations are:

- the supersonic twist / camber / thickness design
- the supersonic design with LE and TE flaps deflected for transonic cruise
- the supersonic dseign with LE flaps deflected for low-speed fly over

Provision has been made for the measurement of overall forces and surface pressures. Because the model is to be tested at high dynamic pressures it was considered essential to modify the manufactured shapes of the transonic and supersonic wings so that in the wind tunnel, under load, the design geometry will be approximately recovered. Calculations to estimate the wing deformation indicated a wing twist of about 1.2° for the supersonic and transonic wing geometries at maximum dynamic pressure. DERA adapted the wing twist of the designed geometry accordingly and provided the modified shape to BAe for final smoothing. Figure 17 shows the geometry of the upper surface of the transonic wing configuration. Planned model delivery date is the end of May with wind-tunnel tests in July 1998. In addition to force and pressure measurements it is planned, if possible, to do some flow visualisation and additional low speed testing, to address the issues noted above.

Analysis and Assessment

All of the computational and experimental data produced during the project will be analysed by a group, led by Aerospatiale, including other industry partners and supported by the research agencies. An assessment will be made of the suitability of the methods and design processes to meet the industrial objectives. As all of the major airframe industry participants in the European supersonic transport activity are members of the EUROSUP consortium the results of the research are immediately available to support project studies.

Concluding remarks

Although the EUROSUP project is not yet complete the results already achieved indicate that considerable progress has been made in the aerodynamic technology to support a second-generation supersonic civil transport. The state of the art aerodynamic analysis and design tools employed have enabled significant improvements to be made in the L/D performance at transonic and supersonic cruise conditions, although these are subject to experimental verification. The situation for the aerodynamic design of the SCT class of configuration is far less satisfactory at low speed - the need for further computational and experimental research in this area has been clearly identified.

Results from the research described are being continuously supplied to industry to support aircraft design. Of particular value are likely to be the automatic methods for dealing with the highly constrained shape design of local regions of complex geometries.

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Partner Activity	DERA	AS	Alenia	BAe	CIRA	DASA	DLR	NLR	ONERA	Saab
Programme co-ord	✓									
CFD evaluation			✓		✓		✓	✓	✓	
Low-speed design	✓		✓	✓						
High-speed design	✓		✓	✓					✓	✓
Low-speed analysis							✓	✓		
High-speed analysis					✓		✓	✓		
Model D, M & test								✓		
W/T data analysis		✓				✓			✓	
Overall assessment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fig 1 EUROSUP partners and research activities

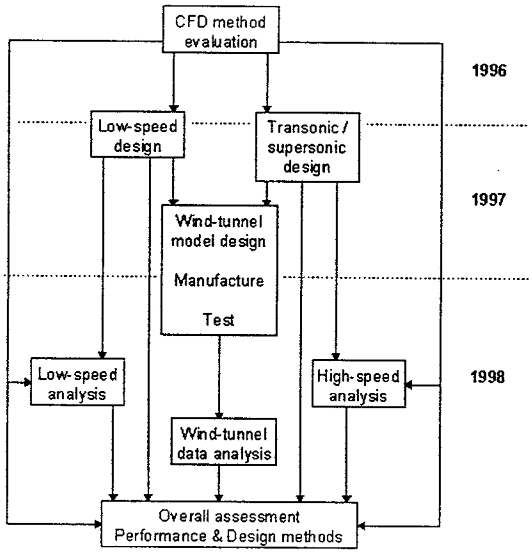


Fig 2 Research task interdependencies

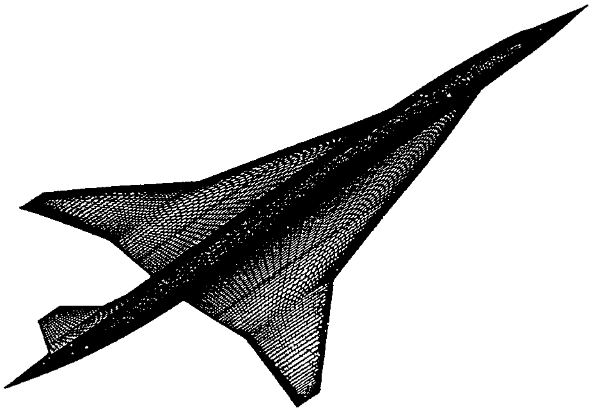


Fig 4 Surface mesh for Euler CFD calculations (ONERA / CIRA)

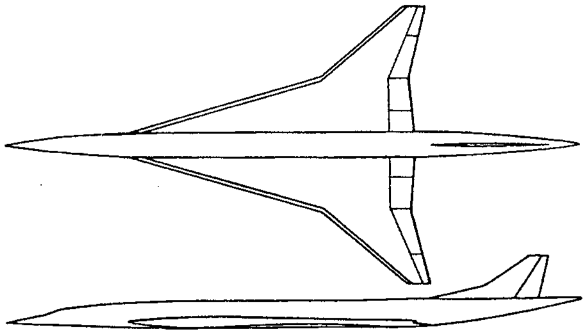


Fig 3 General arrangement of ATSF-1 configuration

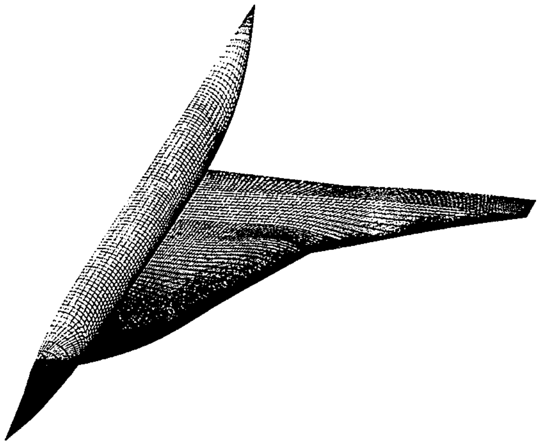


Fig 5 Surface mesh for Navier-Stokes CFD calculations (DLR)

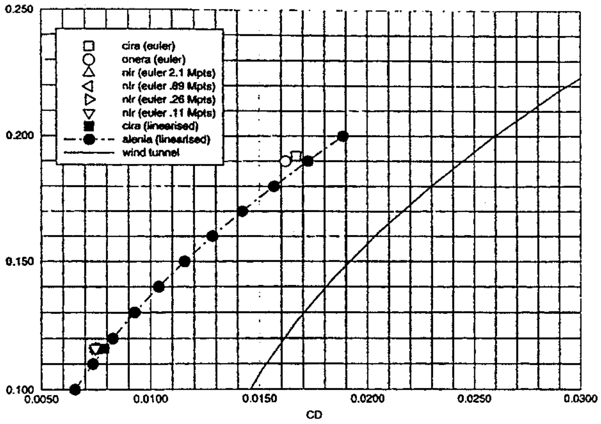


Fig 6 Drag in inviscid supersonic flow (M=2)

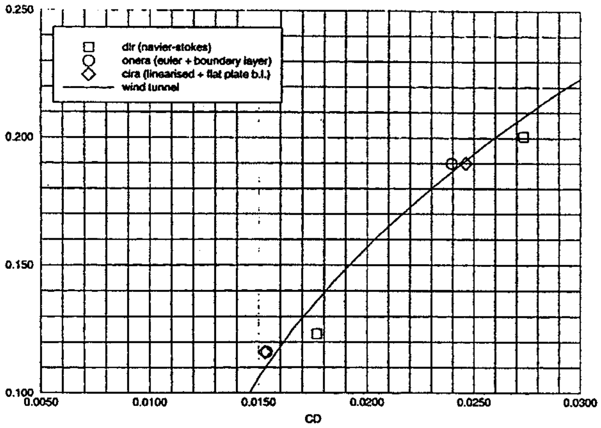


Fig 7 Drag in viscous supersonic flow (M=2)

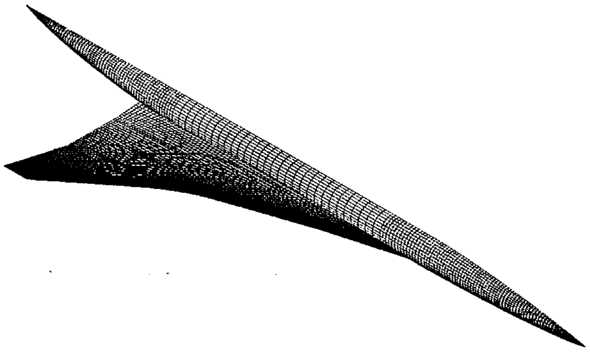


Fig 8 Geometry of the ESCT configuration

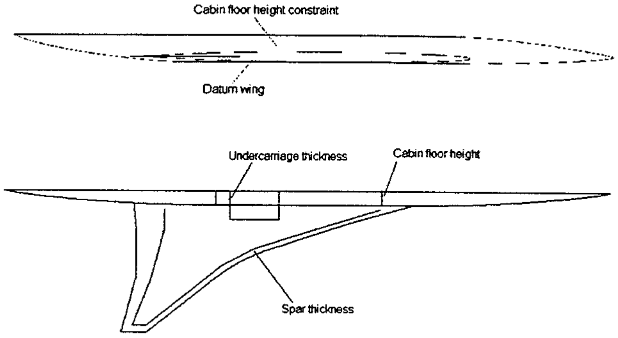


Fig 9 Geometric constraints applied in design

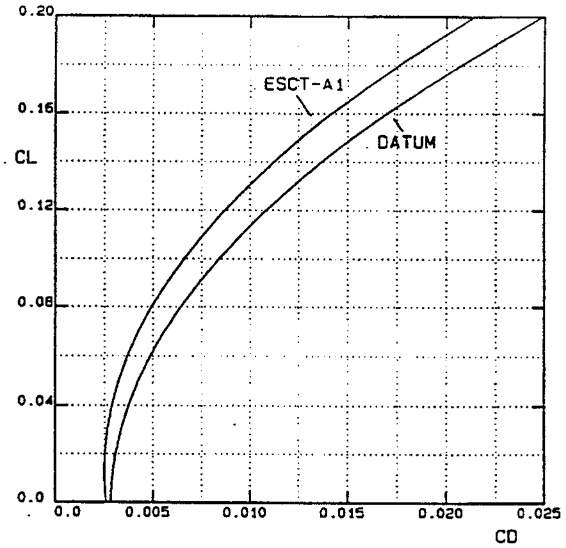


Fig 10 Drag polars for datum and linear-theory design at M=2 (Inviscid, linear-theory analysis: Alenia)

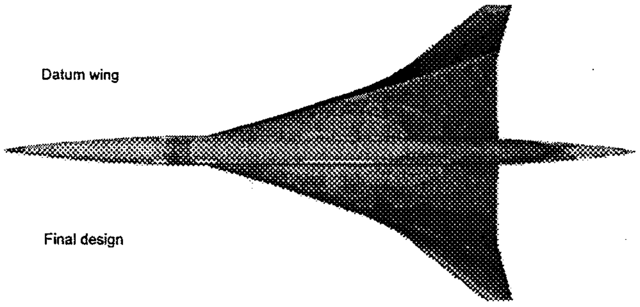


Fig 11 Upper surface Cp for datum and Euler optimisation method at M=2 (ONERA)

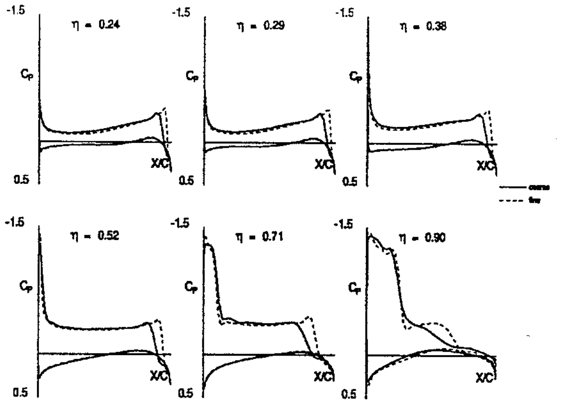


Fig 12 Cp comparison for fine and coarse grids. M=0.95, α=4° (DERA)

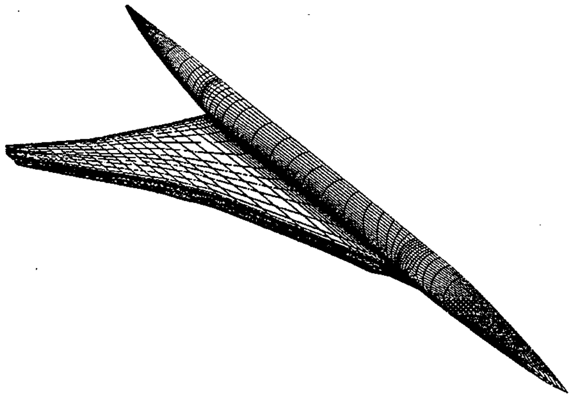
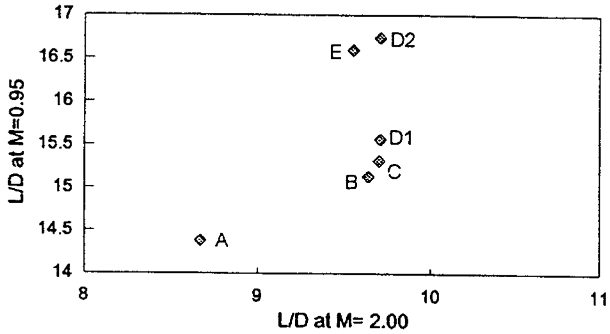
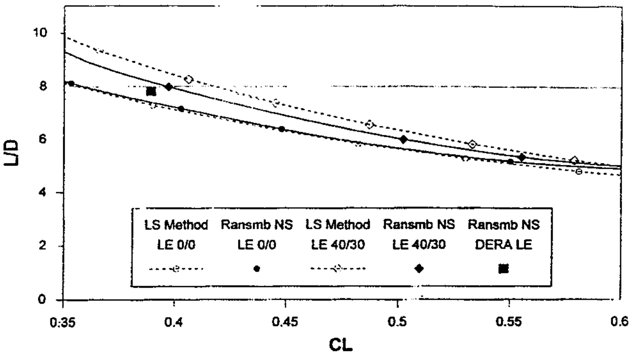


Fig 13 Coarse grid for wing design with deflected leading-edge flaps (DERA)



A - Datum
B - Supersonic design by linear theory (Alenia)
C - Initial supersonic design by Euler optimisation method (ONERA)
D1 - Final supersonic design by Euler optimisation method (DERA)
D2 - Final supersonic design with optimised LE deflection for transonic design point; Euler optimisation method (DERA)
E - Dual -point supersonic / transonic design by Euler optimisation method (DERA)

Fig 14 Summary of results of high-speed design (Euler analysis + skin friction: DERA)



LS method uses a wind-tunnel model experimental data base
Ransmb NS is Reynolds-averaged Navier Stokes multi-block method

Fig 15 Low speed L/D estimates (BAe/DERA)

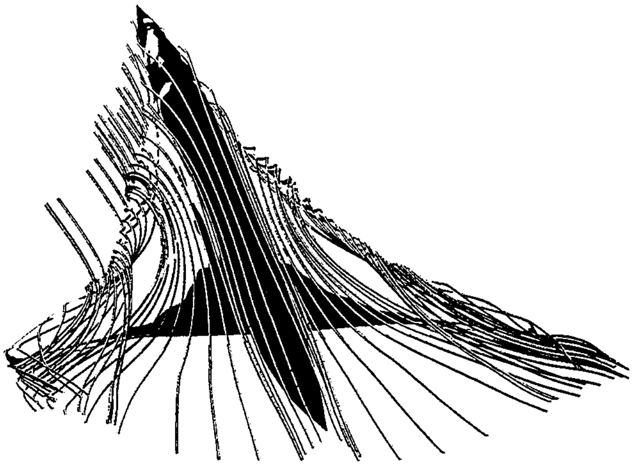


Fig 16 Navier Stokes calculation of low speed flow (DLR)

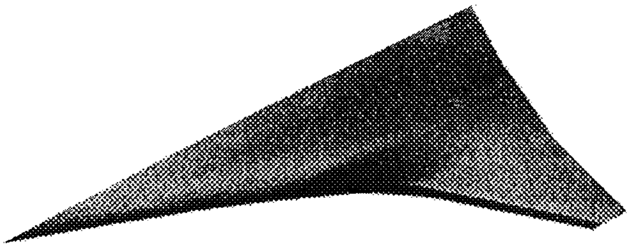


Fig 17 Wing upper surface, transonic configuration (NLR)