AIAA 2004-0769

THE ETW WALL INTERFERENCE ASSESSMENT FOR FULL AND HALF MODELS

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Abstract

The European Transonic Windtunnel (ETW), a pressurized cryogenic facility which in 2003 looked back at 10 years of operation, is offering its clients the testing of full and half models up to flight Reynolds number. Tests are generally performed with those slots in the test section walls opened that are opposite to the upper and lower wing surfaces, thus reducing the wall interference effects to very low levels. Nevertheless, to meet the high data quality standards demanded by aircraft designers, a calibration campaign to determine the small, however not negligible corrections, have been performed for full models in 1998. After development of the half model testing capability with a heated balance mounted behind the test section top wall, this effort has been repeated in 2002, so that the results produced with either test technique can now be considered as equivalent with respect to accuracy.

This paper deals with the general approach to derive the wall interference corrections, outlines the above mentioned calibration campaigns, and compares some test results obtained with a full model and a half model of the same aircraft type.

Introduction

The ETW facility is a high Reynolds number transonic wind tunnel with a working section of 2.0 m × 2.4 m, using nitrogen as test gas. The slots in all walls can be opened or closed in accordance with test requirements. With the use of low temperatures and moderately high pressures, Reynolds numbers up to 50 million at cruise conditions for full span and 90 million for half span models are achieved, representing large transport aircraft (Table 1). The independent variation of pressure and temperature, allowing the separate investigation of Reynolds number and aeroelastic effects, is another outstanding feature of the tunnel.

Test Section	2.4 m x 2.0 m
Mach Number Range	0.15 - 1.3
Pressure Range	1.15 - 4.5 bar
Temperature Range	110 - 313 K
Max. Reynolds Number	50 million *full span models*
Max. Reynolds Number	90 million *half span models*
Mach Number Stability	± 0.001

Table 1: ETW Specification

Although wall-constraint effects are kept low by the use of slotted walls, including subsonic flows with embedded supersonic regions, the residual wall effects have to be corrected before the data can be applied to determine the flight behaviour of aircraft. If the objective is to evaluate Reynolds number effects, accounting for changes of the wall interference with Reynolds and Mach number is absolutely essential in order to avoid wrong conclusions.

A review of the available methods to calculate the wall interference for tests in wind tunnels with slotted-wall working sections in 1996 came to the conclusion, that the classical methods, being based on simplified linear treatment of the wall boundary conditions, did not adequately represent the complex slot flows. Alternative approaches based on measured boundary conditions, avoiding to model the slot flow, did either require some form of model representation, thus violating the requirement of a general applicability, or the knowledge of both normal and streamwise components of velocity at or close to the walls, whereby the normal velocity component is not easily determined by measurement for slotted-wall tunnels. In view of these problems, an alternative method to determine the wall interference for tests at subsonic free-stream velocities was proposed by DERA and accepted by ETW. Four years later the decision was taken to use the same approach for half

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model wall interference corrections, and a contract was placed with QinetiQ, the successor of DERA.

Blockage	$\Delta M = f(M, V_{mod})$
Angle of Incidence	$\Delta\alpha = K_1(M, S_{ref}) \times C_L$
Lift-Dependent Drag	$\Delta C_{D,I} = K_2 \times C_L^2, \quad K_2 = 0$
Buoyancy Drag	$\Delta C_{D,b} = f(M, 1/S_{ref}, V^2_{mod})$
Pitching Moment	
• Zero-Lift Pitching Moment	$\Delta C_{M0} = f(M, S_{ref}, L_{ref})$
• Upwash Gradient Correction	$\Delta C_{ML} = K_3(M, S_{ref}, L_{ref}) \times C_L$

Table 2: Wall Interference Corrections for Slotted Walls

The two calibration campaigns performed at ETW to determine the wall corrections for full and half span models followed the same basic philosophy. However, the taring process used to establish the working section characteristics in the absence of the model, required an increased effort in the case of the full model because of the involved centerline probe and the need to allow for the wall-induced influence associated with the rear supports of the model and the probe. The adopted method for correcting forces, moments and model pressure coefficients uses a technique suggested by C.R. Taylor, formerly at DERA Bedford, which is similar to those used for the 9ft × 8ft Transonic Tunnel at the Aircraft Research Association in Bedford and the NASA Ames 11ft Tunnel. It takes advantage of the fact that the boundary condition for solid-wall wind tunnels is well represented both in classical-type methods and in methods of the Two-Variable type, so that the corrections obtained in the solid-wall working section are based on secure foundations. Using the fully corrected results from tests on a typical model in a solid-wall version (obtained in ETW by closing the slots with special inserts) as a basis, it assesses the wall interference on the same model in the standard, slotted-wall tunnel.

Advantages of the selected approach besides the already mentioned well-established solid-wall corrections are:

- The comparison is made with the same model build connected to the same instrumentation system and with the same model support.
- The basic flow entering the working section is the same for the solid- and slotted-wall configurations.
- The difficulties involved in modeling the slot flow or determining the normal component of velocity close to the wall, as required by other methods, are avoided.

Resulting from the two ETW campaigns to assess the wall interference were two sets of correction coefficients. These have been normalized according to appropriate scaling rules to obtain generalized corrections, which can be applied to models of different size (Table 2).

Brief Review of Methodology

The philosophy of the method to determine the wall interference corrections is illustrated in Figure 1. The same model is tested in both solid- and slotted-wall working sections. Low Reynolds number data are acquired with identical transition fixation in both cases, high Reynolds number data with natural boundary-layer transition. In order to establish the working section characteristics in the absence of the model, two different approaches are used for complete and half models:

- In the case of the sting-supported model, the same centerline probe is tested in both wall

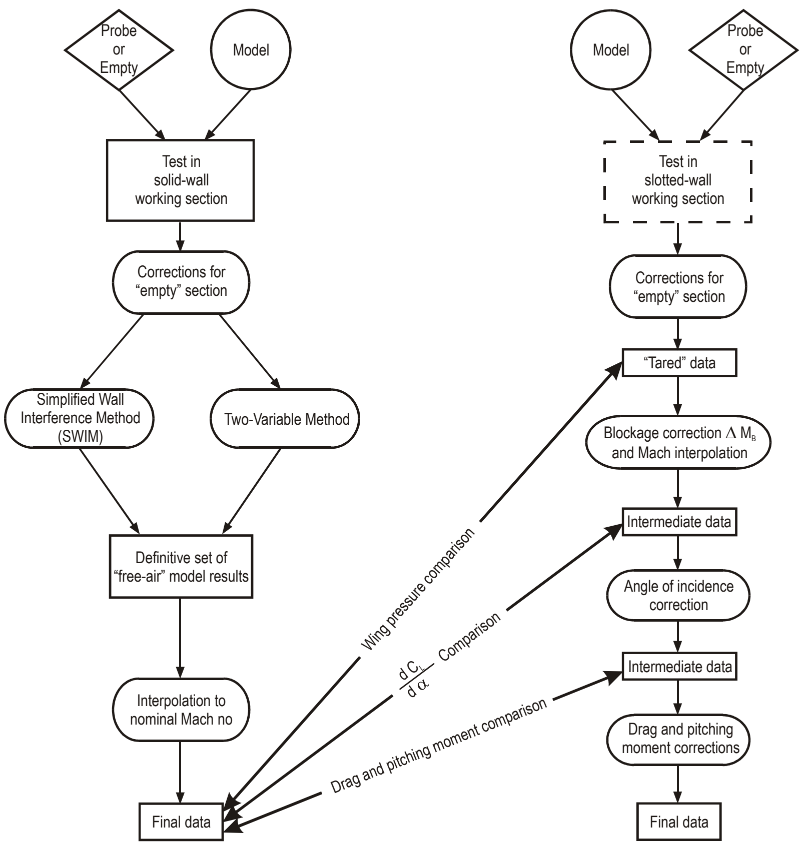

Figure 1: Methodology to Assess the Wall Interference Corrections

configurations. Making the probe support almost identical to that used to support the model, no support effect correction is required; only a small allowance for the nose of the probe has to be made (Figure 2). This definition of “empty tunnel”, which comprises the tunnel together with the rear model sting/support up to the downstream end of the model, has the advantage to allow the isolation of true “model only” effects.

- Since half models are supported from the top wall of the tunnel, only wall pressure data of the empty test section have to be acquired.

Figure 2: Short Axial Probe in the Solid-Wall Working Section

The tests performed in the solid-wall version of the working section are corrected for wall interference by two independent methods, the so-called Simplified Wall Interference Method (SWIM) and the Two-Variable Method. Both rely upon wall pressures “tared” to corresponding data obtained in the “empty” tunnel. Due to the installation of about 425 pressure orifices on all four walls, pressure signatures around and along the entire working section surrounding the model can be measured (Figure 3). The corrected solid-wall data are then compared with data obtained from the same model on the same support in the slotted-wall section which, at this stage, is only corrected to empty tunnel conditions.

To deduce a Mach number correction, carefully selected model pressures near the mid-wing trailing edge, which are reasonably insensitive to variations in angle of incidence, are compared. The next step is then performed on an intermediate slotted-wall data set with the Mach number correction already applied: lift and drag curves are compared to deduce corrections to angle of incidence and lift. Inferring the correction for buoyancy drag from differences in the drag at low lift requires a second intermediate data set, which has in addition been corrected for wall-induced upwash. Finally, the pitching moment results are compared to derive the correction due to the upwash gradient (wall-induced camber) that influences the model in the slotted-wall working section.

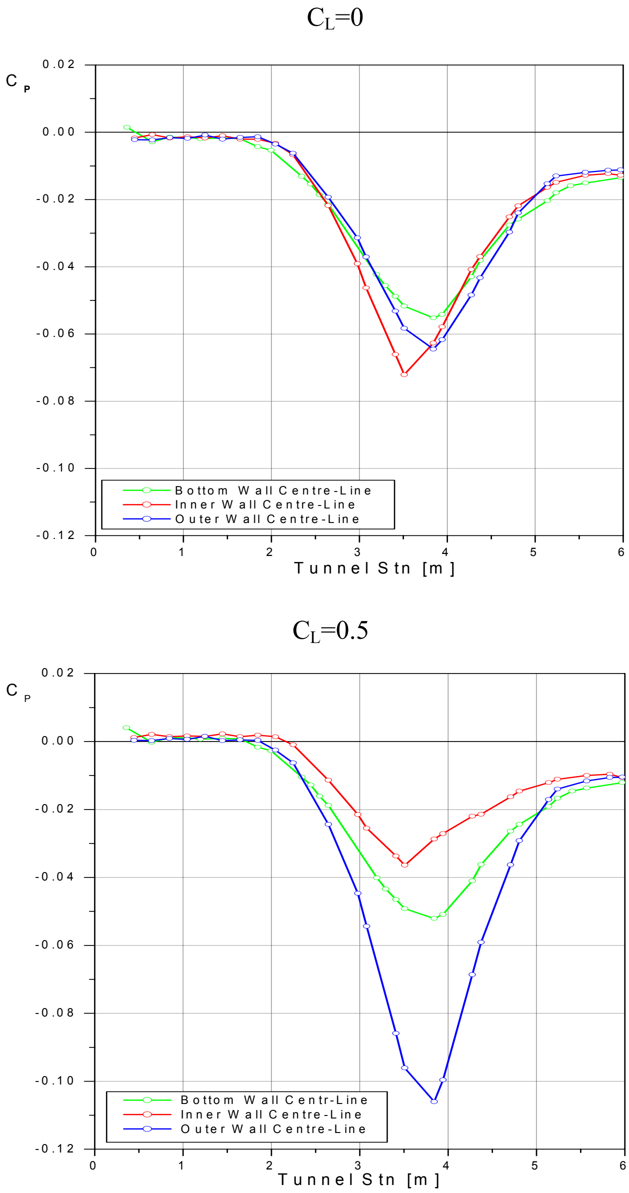

Figure 3: Half Model Signature on Solid Test Section Wall Centre-Lines “Tared” to Empty Test Section

Complete Model Investigations

The standard working section of ETW for complete model tests has solid side walls and slotted top and bottom walls. The six identical slots of constant cross-sectional geometry (approx. 25 mm wide and 6500 mm long) along the top and bottom walls are stretching from the end of the nozzle to the support sector, producing an effective open-area ratio of 3.4% of the total wall surface (visible as dark lines in Figure 4). In the presence of a model, flow leaving the main stream through the slots enters the large plenum chamber. In order to achieve essentially zero pressure gradient along the working section, the straight top and bottom walls are set to diverge both at an angle of 0.55° from the central axis; this standard wall setting having been determined during an earlier calibration phase.

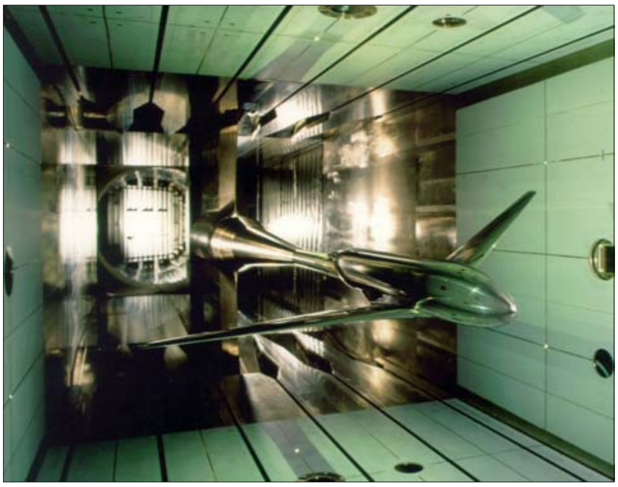

Figure 4: Complete Model in the ETW Test Section

The center-line probe used to create the datum for the full range of Mach and Reynolds numbers, called Short Axial Probe (SAP), was equipped with one row of static pressure holes on the top and one on the side, each containing 37 holes at a regular spacing. Other static holes were installed along the support surface down the centre of both the slotted and solid-wall working section with the SAP present. Since the measurements on the SAP in the vicinity of the model reference centre were used to define the effective free-stream Mach number of the model, corrections had to be applied for the presence of the SAP geometry, mainly the direct-plus-blockage effect of the nose of the probe.

The reference model chosen for the wall interference study consisted of wing, body, fin and flap-track fairings. This configuration remained unchanged throughout the tunnel entry. The model was mounted on the axis of the working section using an ETW owned cryogenic balance and a straight circular sting. Balance and sting axes coincided with the body horizontal datum of the model. In parallel to the overall loads recorded by the six component strain gauge balance, pressure measurements were performed in the base cavity and on the wing. Five chordwise rows of wing pressure taps were located on the port wing and four on the starboard wing, two of the stations being common to both wings. The total number of wing pressure taps was approximately 270, connected to pressure scanners inside the heated compartment in the model nose. The pressures at and downstream of 75% chord on the wing surfaces were connected to a scanner of higher sensitivity, because these were intended to be used as potential local Mach number indicators.

Tests with the center-line probe as well as the model were performed at three different Reynolds numbers, the latter being maintained constant over the Mach number range by holding the temperature constant and reducing the stagnation pressure (and hence the dynamic pressure) with increasing Mach number. The model tests at low Reynolds number were deliberately done at the end of the solid-wall series, so that the transition bands remained intact for the corresponding low Reynolds-number test at the start of the slotted-wall programme. In order to avoid any uncertainties due to different filter or - in the case of long pressure tubes - unknown tube response characteristics, the so-called pitch/pause mode was used for all incidence traverses, i.e. after each incremental change of the incidence angle the model movement was suspended and fifteen samples of data were recorded, averaged in the data reduction and output as a single data point.

As mentioned before, two independent methods were used to determine the wall corrections in the solid wall wind tunnel, both relying on measured wall pressure data. The Simplified Wall Interference Method involves a model representation using linear potential-flow theory, whereas the Two-Variable Method needs no knowledge of the model geometry. Instead it requires detailed information of the velocity perturbations on the walls. It could be shown, that the results obtained with both methods were in excellent agreement. Now a definitive set of aerodynamic characteristics could be derived for the model, based on which the corrections in the slotted wall tunnel could be inferred from comparisons of wing pressures and overall model loads. The essential prerequisite for this approach to be successful was, that the measurement precision and data repeatability were sufficient to determine the small corrections to the data in the slotted-wall working section.

Following the steps outlined in the preceding paragraph, wall-constraint corrections within the accuracy limits of the expected measurement precision were obtained, demonstrating a high degree of consistency. Since the objective of the calibration campaign was to produce a set of correction coefficients not just valid for a single model, but for a variety of models of different sizes, considerations had to be given to its generalization. This goal was reached by defining appropriate scaling rules for each correction.

The general applicability of the complete model wall interference corrections, at least concerning the transport aircraft type, was confirmed by the outcome of the European research project HiReTT (High Reynolds Number Tools and Techniques), part of which comprised of a test with the same model on the same sting in ETW and the ONERA S1 tunnel, the latter being regarded as wall interference-free due to its large test section dimensions, and two semi-empirical approaches to assess the wall interference in the slotted-wall working section of ETW with emphasis on Mach numbers above 0.8. No indications were found that either the method itself or the correction coefficients might be questionable.

Half Model Investigations

Having developed the half model testing capability, an exercise similar to that for complete models has been performed in 2002, motivated by the need to determine the wall interference corrections for the slotted wall working section. As in the case of the complete model, a generic transport-aircraft type was selected for the study.

The decision for a test section with a solid floor and sidewalls each with four longitudinal slots was based on the results of a preliminary investigation in the Pilot version of the wind tunnel (PETW). This wall configuration is characterized by a very low axial pressure gradient, which is also mainly independent of Mach and Reynolds number.

The four identical, longitudinal slots on each sidewall are 6070 mm long (visible as dark lines in Figure 5). At the streamwise extremities, they taper from 5 mm at the end to 37 mm over a length of 611 mm, giving a taper angle of 1.5°, resulting in an effective open area of 4.625% relative to the total surface area of the working section. The bottom wall is set to diverge by an angle of 0.55° relative to the tunnel centre-line in order to compensate for the pressure gradient generated by the tunnel walls. Adjustable finger flaps are used to trim the flow downstream of the re-entry point.

In view of the growing demand for half model testing in conjunction with an emphasis on either low or increasingly high Mach numbers (Ref. [1,2]), ETW decided to establish the slotted-wall corrections for the complete subsonic range from M=0.2 to a Mach number well above M=0.9, covering the full spectrum of pressure and temperature conditions. Tests were performed at seven different Reynolds numbers, which were maintained constant by keeping the temperature constant and reducing the stagnation pressure with increasing Mach number, as shown in Figure 6 (identical Reynolds numbers are represented by the same colour).

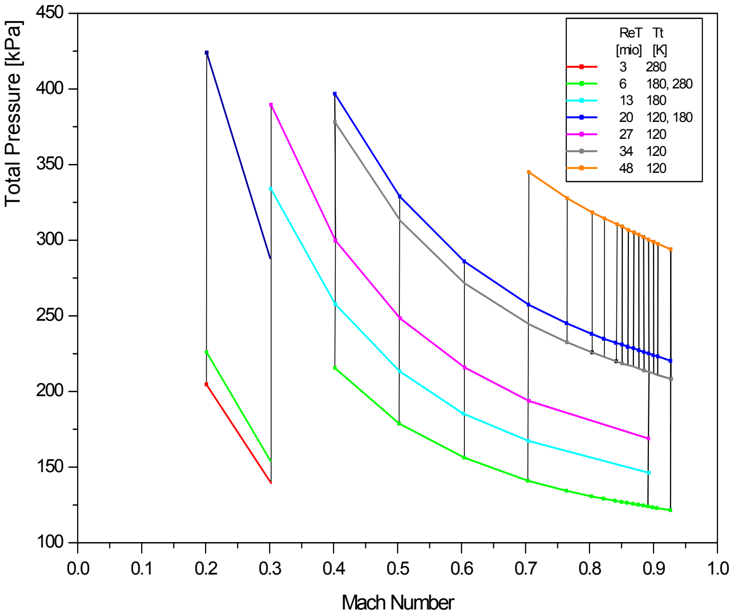

Figure 6: Envelope of Tunnel Test Conditions

Figure 5: Half Model in the ETW Test Section

The half model chosen for the wall interference study was a 1/30th scale version of the model used in the HiReTT project, consisting of wing, fuselage, belly fairing and plinth. The plinth, of 20 mm thickness, was applied between the tunnel top wall and the half model symmetry plane to prevent the boundary layer of the working section roof affecting the flow over the body. The only change to the model throughout the campaign was the application of transition bands for low Reynolds number testing in both working sections which were removed for the tests at higher Reynolds numbers.

The model, mounted on the thermally conditioned half model balance, was supported from the top wall with its reference plane coincident with the test section centre-line at zero incidence angle. In addition to the loads measured by the balance, static pressure measurements were made simultaneously on the wing and body. The wing pressure taps were arranged in seven sections, each comprising of 35 holes, which were dispersed chordwise on the upper and lower surfaces of the wing.

Mach and Reynolds number conditions for the empty tunnel tests corresponded exactly to the model-in test conditions, both for the solid and slotted-wall working sections. This effort was required in order to determine the differences of the static pressure between the tunnel reference pressure measurement points and the model reference point, and to allow the "taring" of the wall pressures in the solid-wall case.

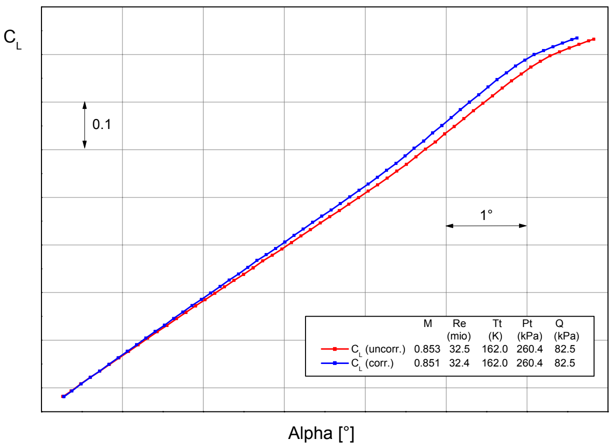

Figure 7: Uncorrected/Corrected Lift Coefficient C_L as Function of Incidence Angle α

As in the case of the complete model, the corrections to Mach number, angle of incidence, drag and pitching moment were found to be small but significant. No noticeable trends with either lift coefficient or Reynolds number could be determined, however a significant Mach number trend. The half model corrections are in fact slightly higher than those of the complete model.

Figure 7 shows the uncorrected and corrected lift curves of the reference model used in the study at cruise speed. The incidence angle correction at C_L=0.5 is approximately 0.15°, and the Mach number correction 0.002.

Comparison of Full/Half Model Results

The same type of aircraft was selected as reference half model for the wall interference assessment, that had been used in the HiReTT European research project and for which ETW had already acquired an extensive data base with a complete model version. Since the model designers also took great care to reproduce the mechanical properties of the complete model, this presented the unique opportunity to compare full and half model results at a variety of identical test conditions.

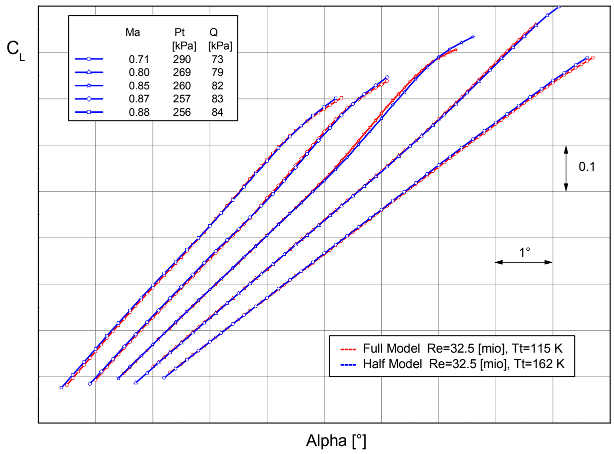

Figure 8: Lift Coefficient C_L vs. Incidence Angle α (Graphs Staggered in Increments Δα = -0.5°)

Unfortunately, the different model support types and the different fuselage design (e.g. the plinth applied between tunnel top wall and half model symmetry plane) reduce the characteristics suited for direct comparison considerably. One of them is the lift, which is largely dominated by the wing with only a minor contribution by the fuselage. Figure 8 shows the lift coefficient vs. incidence angle at a constant Reynolds number of 32.7 million for five different Mach numbers. The highest depicted Mach number corresponds to the highest Mach

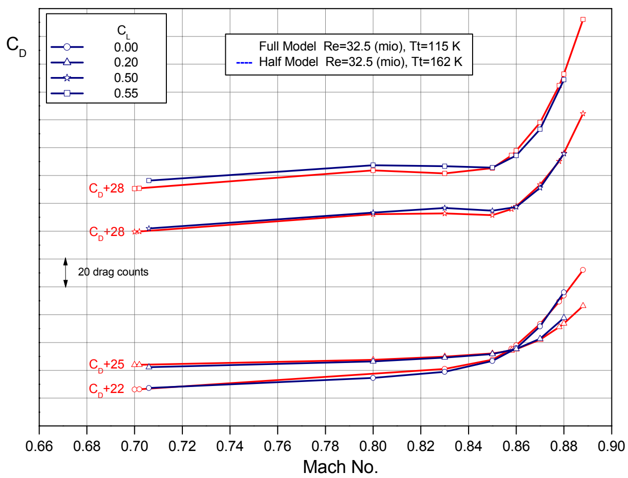

Figure 9: Drag Coefficient C_D vs. Mach Number (Increments ΔC_D Added to Complete Model Values)

number at which both models have been tested and for which interpolation to nominal Mach number could be performed.

Although the absolute drag level is one of those characteristics which do not lend themselves to direct comparison between complete and half models, its Mach number trend is however an interesting issue which is in addition well suited for comparison. Shown in Figure 9 are the drag coefficients for Mach numbers from 0.7 to 0.89 at four constant lift coefficients, ranging from zero lift to C_L=0.55. Constant increments of 22 to 28 drag counts have been added to each curve of the complete model to match the corresponding one of the half model.

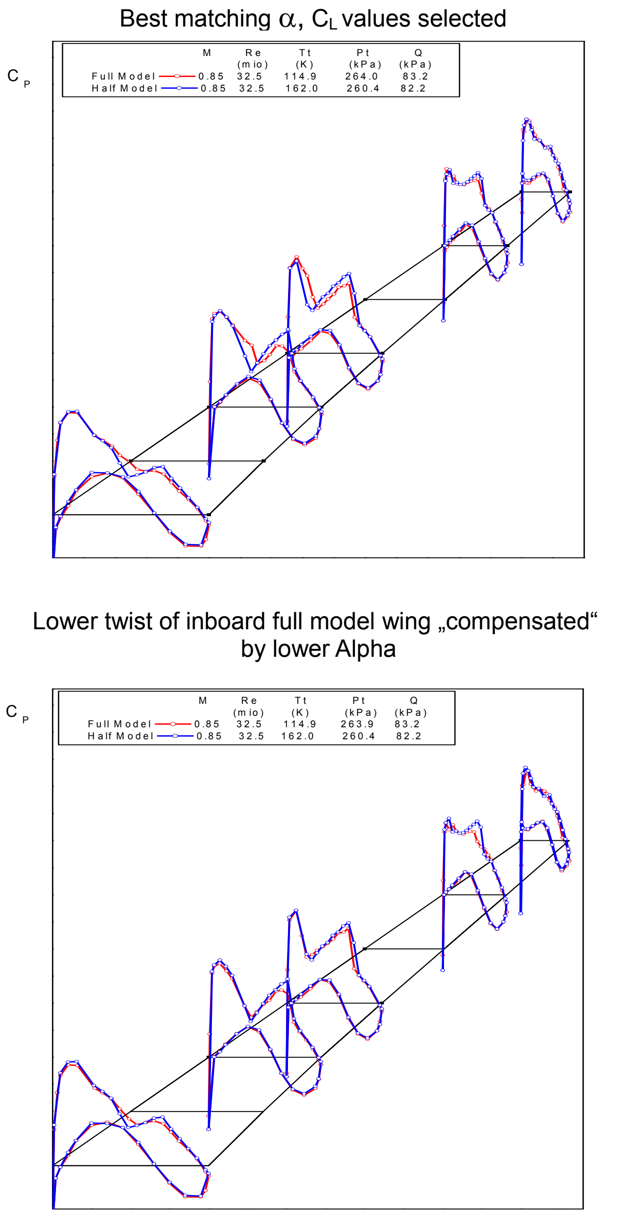

Figure 10: Wing Pressure Distribution at Cruising Conditions, Re=32.5 million

Looking at the pressure distribution of five wing sections located at the same relative spanwise positions, measured at cruising speed (Figure 10), the first impression is that despite having selected the closest incidence angles and lift coefficients from both data sets the match at the inboard stations is relatively poor. Having performed a wing twist assessment using the approach developed by ETW to deduce the twist from its effect on the local wing pressures by comparing data acquired at different tunnel pressures (Ref. [3]), it became however evident that despite tremendous efforts to achieve identical test conditions, the twist of the inner half model wing was in fact slightly higher than that of the complete model (Figure 11). In that case, selecting a pressure distribution of the complete model at a slightly reduced incidence angle to simulate a higher twist, should improve the match at the inner sections while the differences at the outer sections should increase. Since this exercise indeed yielded the expected result, a small difference in the elastic deformation of the two wings is likely to be the right explanation for the observed pressure differences.

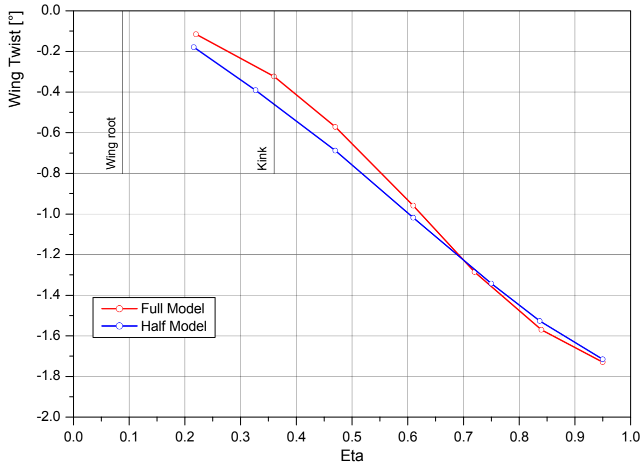

Figure 11: Wing Twist of Complete and Half Model at Test Conditions Shown in Figure 10

Concluding Remarks

Two campaigns have been performed by ETW to determine the wall-constraint corrections for complete and half models in the slotted-wall working section of the wind tunnel. In both cases, the corrections to Mach number, angle of incidence, drag and pitching moment were found to be small. The approach to infer the corrections from the comparison of slotted-wall data with fully corrected solid-wall data demanded an excellent measurement precision and repeatability in order to be successful. These requirements have been met throughout the campaigns by deliberate planning and consistency of the model, balance, instrumentation and tunnel-operating conditions, thus maintaining a high data quality standard.

Confidence in the general applicability of the complete model wall interference corrections has been gained by the outcome of the European research project HiReTT (High Reynolds Number Tools and Techniques), which confirmed the validity of the corrections and the assessment method.

The results of comparing full and half model data, made possible by the selection of the same aircraft type as reference half model for the wall interference assessment, of which the complete model version had been extensively tested in the course of the HiReTT project, allow to conclude that both test techniques are equivalent with respect to data accuracy and repeatability.

Acknowledgements

The authors would like to acknowledge Prof. P.R. Ashill and his team at QinetiQ (formerly DERA) for successfully accomplishing the complete and half model wall interference studies, and for the fruitful discussions and recommendations concerning the execution of the wind tunnel tests.

The HiReTT project (High Reynolds Number Tools and Testing) has been partly funded by the European Commission within the 5th framework programme and coordinated by Airbus UK. A large number of different collaborators from the European industry and European research establishments, to whom the authors wish to express their gratitude, were engaged in the validation process of the ETW wall interference corrections.

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