INTERFERENCE DETERMINATION FOR THREE-DIMENSIONAL FLOWS IN SLOTTED- LINER WIND TUNNELS

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ABSTRACT

Results from two sets of tests made with a swept wing model mounted in a low speed wind tunnel are presented. The first set utilised a solid liner test section, whilst the second employed slotted floor and roof liners. Wall-induced interference calculated using the measured boundary condition method of Ashill and Weeks is presented for both sets. Comparisons are made of wing pressure and lift data, corrected for the effects of wall-induced interference, and, together with theoretical results for the solid liner lift interference, indicate that interference is determined from use of the Ashill and Weeks approach to an accuracy of the order 0.05 deg in upwash and 0.002 in blockage. Some consideration is given, based on both the present and earlier tests, to the use of a similar approach for determining wall interference in large transonic wind tunnels with slotted liners.

1. INTRODUCTION

A scheme for determining wall-induced interference in slotted-liner wind tunnels is presented and assessed using tests at low speed with a swept wing model. The present work extends earlier studies (References 1,2) with two-dimensional models which included both low speed and transonic flow investigations. The intended application of the scheme is principally to three-dimensional tests at transonic speeds in slotted-liner wind tunnels such as the European Transonic Wind Tunnel (ETW), where very precisely determined wall interference is required.

The scheme has for its theoretical basis the work of Ashill and Weeks (Reference 3), which established how wall interference may be determined from surface integrals involving distributions of the longitudinal and normal velocity components, u and v_n, of the effective inviscid flow (EIF) over the test section boundary. For rectangular test sections with solid wall liners, v_n may be taken as zero (although, ideally, a small correction for boundary layer growth has to be considered), and distributions of u may be found from sufficiently detailed measurements of wall static pressure. In References 3 and 4 several solid liner applications of the Ashill and Weeks method are given, which establish the utility and accuracy of the approach for such wind tunnels.

For slotted liner test sections, which are of particular interest for transonic flows, the implementation of the Ashill and Weeks approach is not so straightforward as for solid liner test sections, since the flow into and out of the slots affects v_n, which may no longer be taken to be close to zero.

In References 1 and 2, successful applications of the Ashill and Weeks approach are described for slotted-liner test sections. For slot flows which do not produce significant disturbance of the liner shear layers, it was shown to be sufficient to determine the normal velocity along the centre of each slot, and to use this as a direct indication of the EIF slot mass flux. In Reference 2, some flows required the shear layer disturbances to be taken into account. These related to slot flows where air was returning from the plenum chamber to the test section, and the shear layer disturbances produced were probably more severe than would occur in a transonic wind tunnel test of a three-dimensional configuration. In any event it is expected that the occurrence of such slot flows could be identified and adequate allowance made for them.

In Reference 1, a theoretical treatment of slot flow was developed, which showed promise as a means of reducing the number of measurements required to yield an adequate distribution of slot mass flux. However the present work utilises only measured slot flux distributions.

In common with the approach of References 1 and 2, two sets of tests are conducted, identical apart from the liner configuration. Tests with solid wall liners serve as a means of establishing a standard of comparison for the subsequent slotted liner tests.

2. NOTATION

a	maximum slot width (20mm)
a'	sectional (corrected) lift curve slope
B	working section width (546mm)
C_{LLc}	local lift coefficient corrected for blockage
C_{LLm}	measured (i.e. uncorrected) local lift coefficient
C_{pc}	pressure coefficient corrected for blockage
C_{pu}	measured (i.e. uncorrected) pressure coefficient, $(p - p_{ref})/1/2\rho U_{ref}^2$
c	wing chord (229 mm)
H	working section height (394 mm)
h	slot depth (17 mm)
L	overall slot length (914 mm)
$L1$	length of forward slot taper (229 mm)
$L2$	length of rearward slot taper (152 mm)
p	local static pressure
p_{ref}	static pressure at wind tunnel reference position
s	wing span (437 mm), $= 0.8B$
$\bar{U}$	wind speed infinitely far upstream (i.e. in absence of blockage)
U_{ref}	wind speed at reference position
u	longitudinal velocity component
u'	wall-induced longitudinal velocity, divided by $\bar{U}$
u'_r	value of u' at wind tunnel reference position
U_c	local corrected longitudinal velocity
v	lateral velocity component
v'	wall-induced lateral velocity, divided by $\bar{U}$
v_s	mean normal velocity component over width of slot
w	vertical velocity component
w'	wall-induced vertical velocity, divided by $\bar{U}$
x,y,z	Cartesian coordinates with origin at wing apex at mid test section height, see Figure 1
a_c	(local) corrected wing incidence
a_c'	value of a_c at local 3/4 chord position
a_g	geometric wing incidence
δa	incidence correction, $= a_c - a_g$
η	y/s
ξ	$(x - x_{le})/c$
ρ	density (effectively uniform in low speed flow)
Suffices	
L	denotes lower surface of wing
le	denotes (local) leading edge value
U	denotes upper surface of wing

3. EXPERIMENTAL CONSIDERATIONS

Although the intended main application of the scheme is for transonic flows, tests at low speed provide a valuable means of assessing both the difficuties and the potential of applying the Ashill and Weeks measured boundary condition method for three-dimensional tests. In order to ease the problem of discriminating between various small influences, a relatively large model wing was used in the present tests, see Figure 1. The wing was mounted on the sidewall ($y=0$), and had a constant chord of 229 mm, a span of 437 mm, a uniform aerofoil section (NACA 0015), and zero twist. Wing sweep was 25 deg. A boundary layer fence was installed near the wing root, at $y=30$ mm, see Figure 2. Three sections were pressure tapped, at $\eta = 0.339$, 0.625 and 0.911, giving 87 wing pressure measurements. The tunnel working section (394 mmm high, 546 mm wide and 2000mm long) resulted in $H/c = 1.72$ and $s/B = 0.8$. In the slotted liner tests, the roof and floor of the test section each had four longitudinal slots, tapered linearly in width over the upstream quarter ($L1$) and downstream sixth ($L2$) of their length, with a width between the tapered portions of 20 mm, giving a nominal open area ratio there of 15 per cent. Such a large value of open area ratio is needed in order to keep the normal slot velocity to levels (less than $0.3U_{ref}$, approximately) representative of ETW tests. The air removed from the test section, through the slots, passed through controlled fans located above and below the plenum chambers and returned to the wind tunnel circuit at the diffuser - well aft of the working section. The slot form is typical of most slotted liner wind tunnels apart from the rear taper which was adopted for the present tests as it provides a slot mass flux that approaches zero regularly at both upstream and downstream extremities, thus removing one source of uncertainty in the test boundary conditions.

In the solid liner tests, a total of 180 pressure tappings were provided in the floor ($z=-197$ mm), roof ($z=197$ mm) and sidewall ($y = 546$ mm). For the subsequent tests, the slotted roof and floor liners were each equipped with five rows of tappings, see Figure 2, and, together with the tapped sidewall, provided 192 pressure measurements on the test section boundary. Special care was taken in providing high quality pressure tappings, and in measuring pressures accurately. In each test the reference conditions were determined from a sidewall mounted pitot-static tube located at $x/H=-1.6$. Detailed slot flow measurements were made using a pitch/yaw probe which was traversed along the centre line of each floor slot. Flows relating to the roof slots at positive wing incidence were obtained from floor slot traverses at equal negative incidence, following checks on the relevant pressure distributions. Tests were made at $\alpha_g = 0, 2, 4$, and 6 deg at a reference wind speed of 28 ms^{-1}, (giving a Reynolds number based on wing chord close to 0.45×10^6). No means of fixing boundary layer transition were employed.

4. INTERFERENCE DETERMINATION AND CORRECTIONS

Distributions of u', v' and w' throughout the test section were obtained from a program, SLOT3, written during the course of the present work, which implements the method of Reference 3 for slotted liner test sections. The effects of the slot flows on the interference flow fields are modelled in the program by line sources of varying intensity located along the slot centre lines. The adequacy of concentrating the mass flux in this way was checked by noting that there were no discernible effects on interference velocities in the plane $z=0$ resulting from displacing the sources laterally to either edge of a slot. Singularities representing the u disturbances were obtained from wall C_{pu} measurements, with values at positions intermediate between tapping locations being found from linear interpolation. It was considered that any adjustment to the boundary pressures to allow for variation across a slat and slot produced by the local slot flux would be negligible for the slot flows of the present tests, although such an adjustment could fairly readily be incorporated, see Reference 5. Variations of the magnitude and longitudinal extent of the (extrapolated) singularity distributions representing the u disturbances downstream of the test section were studied, and it was found that interference velocities in the region of the model were effectively the same for all reasonable extrapolations. For the current tests, symmetry of the flow fields about the plane $y=0$ was assumed, so no conditions measured on the sidewall in this plane were required or imposed. Evaluation of interference, using SLOT3, required only a few seconds of computing time to yield a detailed distribution.

4.1 Pressure Coefficient Corrections

Correction to the value of pressure coefficient, C_{pu}, allows for the interference flow producing a higher value of effective wind speed at the model location (with positive blockage) than occurs at the reference location. With the effective wind speed at the model location equal to $\bar{U}(1 + u')$ and the speed at the reference position, U_{ref}, equal to $\bar{U}(1 + u_r')$, it is found that

$$C_{pc} = f C_{pu} + (1 - f), \qquad (1)$$

where $f = ((1 + u_r')/(1 + u'))^2$.

When u' and u'_r are initially evaluated, using SLOT3 in the present case, $\bar{U}$ is not known. An initial value of U_{ref} may be taken for $\bar{U}$, and this can be iteratively corrected at a subsequent stage. In the present tests u_r' amounted to 0.007, approximately, for both solid and slotted liner runs, and was thus not negligible.

Corrections for blockage are strictly well founded only when u' is uniform in the region of the the model. However, with a linear variation of u' with x, it can be shown that corrections to C_{pu} based on the local values of blockage result in pressure coefficients very close to those corresponding to free air flow. For this reason, corrections to C_{pu} using Equation (1) with u' set to its local value are employed. In the solid liner tests to be described it was found that variations of about 0.015 in u' occurred over the wing planform. For the slotted liner tests the variations were only about 0.005. These variations are higher than normal as a result of the untypically large size of the model relative to the wind tunnel test section.

4.2 Corrections to lift coefficient and incidence

Having obtained corrected values of wing pressure coefficient, C_{pc}, these may be integrated to yield the corrected local lift coefficient, thus:

$$C_{LL_c} = \int_0^1 (C_{pcL} - C_{pcU})\, d\xi \; . \qquad (2)$$

If the wall-induced upwash and blockage were uniform in the region of the wing, then there would be a correction to incidence

$$\delta\alpha = \alpha_c - \alpha_g = w / U_c \; . \qquad (3)$$

In two-dimensional flows, a linear variation of w over the chord results in the wing section producing the same distribution of lift over the chord as that of a section with an additional parabolic camber placed in a uniform stream. The same lift coefficient is produced as on the original section if the incidence correction $\delta\alpha$ is evaluated at the 3/4 chord location and the induced camber otherwise ignored. In the analysis of the present tests the variations of w over the chord are very nearly linear, and the incidence at the local 3/4 chord position is adopted as the basis of comparison of C_{LL_c} values determined for the solid and slotted liner tests.

5. TEST RESULTS AND ANALYSIS

5.1 Solid liner tests

Pressure measurements were first made on the swept wing model with the solid liners installed. These were corrected for wall-induced blockage as described in Section 4.1. The interference velocity fields were determined from measurements of wall pressures using the program SLOT3 with no slot flow representation. Typical liner pressure variations are shown in Figure 3. The resulting variations of the interference velocity components u' and w' with x are shown (in the plane $z=0$) for $\eta = 0$, 0.339, 0.625, and 0.911 in Figure 4. The wing extends from $x=0$ (at the apex) to $x/H=1.1$ (tip trailing edge). It is seen that u' at a particular location hardly changes with incidence, which accords with blockage being the consequence of model displacement and viscous drag. Variations of w' with α_g are shown in Figure 5 where it is seen that values of w' lie within ± 0.0005 of a straight line. This suggests that the levels of accuracy of determining interference flow field angles from wall pressures in the present tests are of the order ± 0.03 deg. It is noted that there is a small amount of upwash even at $\alpha_g=0$.

Examples of uncorrected and corrected wing pressure coefficients are shown in Figure 6. The pressures on the upper and lower surfaces differ slightly at $\alpha_g=0$, and indicate some minor imperfection in the wing model manufacture. This is of little consequence in the present tests where the objective is to assess the effects of different wall liners. Comparing the C_{pc} values with those given in Reference 1, obtained on an unswept wing of the same section spanning the working section, there is a good correspondence, provided the known effects of sweep and finite span are taken into account.

Corrected local lift coefficients are shown in Figure 7, plotted against α_c evaluated at the local 3/4 chord position, α_c'. Compared to free air, the incidence angle at this location, at each of the three spanwise locations, is increased by about 22 per cent. A vortex-lattice program written to determine the theoretical lift interference in a solid liner wind tunnel produced a value for this increase which varied between 24 percent and 21 per cent across the wing span. This good agreement with three-dimensional linear theory may be taken as a further indication that wall-induced interference is being accurately obtained.

5.2 Slotted liner tests and comparison with solid liner results

With the solid roof and floor liners replaced by slotted liners, the second series of tests was conducted. In addition to liner static pressure measurements, slot normal velocity distributions were obtained using remotely-controlled traverses of a calibrated flow angle probe along the centre line of each slot. Some results from these boundary measurements are shown in Figure 8. Utilising these data as input to SLOT3 resulted in the distributions of the interference velocity components u' and w' shown in Figure 9. It is seen that the blockage levels determined for the slotted liner tests are considerably lower than the corresponding levels with solid liners (Figure 4). As with the solid liners the blockage is very little affected by change of wing incidence. With slotted liners fitted the blockage varies much less over the region occupied by the model. The induced upwash is also significantly lower with slotted liners installed. Variations of w' with a_g are shown in Figure 10, which may be compared with the correponding variations with solid liners given in Figure 4. The regular behaviour seen in Figure 10, with differences from smooth variations being as low as ± 0.0005, suggests that the induced upwash is determined as accurately in the slotted liner tests as in the solid liner tests. The direct contributions of the slot flows to the u' and w' distributions are shown, for $a_g = 6$ deg, in Figure 11. Although these contributions are relatively small, it is seen that they serve to reduce the variations of both the longitudinal and vertical interference velocity components over the model region.

In Figure 12 corrected wing pressure coefficients for the slotted liner tests at $a_g = 0$ deg are shown and are compared with the corresponding C_{pc} data from the solid liner tests. No differences between the two sets of results may be discerned in Figure 12(i). Examining the numerical data reveals differences in C_{pc} values to be at most 0.015. Near the trailing edge, where the values of C_{pc} are small, differences would be dominated by inaccuracies in the determination of blockage (in one or both of the sets of tests). In this region differences between corresponding C_{pc} values are as low as 0.004, indicating that evaluation of blockage velocity is consistent between the solid and slotted liner tests to about 0.002 in u'. Changes to C_{pc} resulting from blockage correction are of the order of 0.1, and are thus sufficiently large to provide a searching test of the ability to obtain the blockage accurately.

In Figure 13, values of C_{LL_c} are plotted against a_c', for each of the three pressure tapped wing sections. It is seen that the variations are close to linear. The least-square straight line fits to these variations have slopes, a', as shown in Table 1, where the results for solid liner tests are also given for comparison (these correspond to the data of Figure 7).

Table 1 Lift curve slopes from solid and slotted liner tests

η	0.339	0.625	0.911
a' (solid) deg^{-1}	0.0574	0.0536	0.0347
a' (slotted) deg^{-1}	0.0567	0.0531	0.0347
a' (solid)/a' (slotted)	1.012	1.009	1.000

The differences between solid and slotted liner lift-curve slopes are seen to be of the order of 1 per cent, which strongly suggests that the solid and slotted liner wall-induced upwash distributions are being determined in the two wind tunnel configurations to a very similar level of accuracy. It should be noted that allowing for wall-induced upwash changes the lift-curve slopes by about 22 per cent, so to get agreement in the corrected values of such slopes to about 1 per cent indicates that upwash is being evaluated to an accuracy of about 5 per cent or about 0.05 deg in terms of flow angles. Also, part of the small differences in lift curve slope that are found could be due to the fact that the C_{LL_c} values are derived from integrations of upper and lower surface pressures measured at relatively few points, so the actual evaluation of interference velocities could well be somewhat better than 5 per cent.

6. CONCLUDING REMARKS

The analysis of the experiments described above indicates that the boundary value method of Ashill and Weeks may be used in practice for three-dimensional model configurations tested in slotted- as well as solid-liner test sections and yields interference velocity fields of similar accuracy in the two cases.

The present application to slotted liner wind-tunnel tests utilises slot traverses, but such traverses could readily be substituted by a number of fixed flow angle probes. The smallest numbers of such probes and of the wall static pressure tappings, needed for accuracy in the application of the method, require to be critically assessed, but in any case would not appear to be excessive for a large scale wind tunnel. The amount of computation to evaluate the surface integrals of the Ashill and Weeks method for any given test run is trivial with current computing facilities.

Earlier work (Reference 2) indicated that extension from low-speed to transonic flow should produce no additional difficulty in application, provided the slot flows involved produce no large shear layer disturbances. Even were such large disturbances to be produced, means of accounting for them could be adopted.

7. ACKNOWLEDGEMENTS

The work presented was supported by the Department of Trade and Industry, and this is gratefully acknowledged. Encouragement and advice given by Dr P R Ashill, who acted as technical monitor, are highly valued. Technical assistance of a high standard was given by Mr M Smith and Mr C Barber, of the Centre for Aeronautics.

8. REFERENCES

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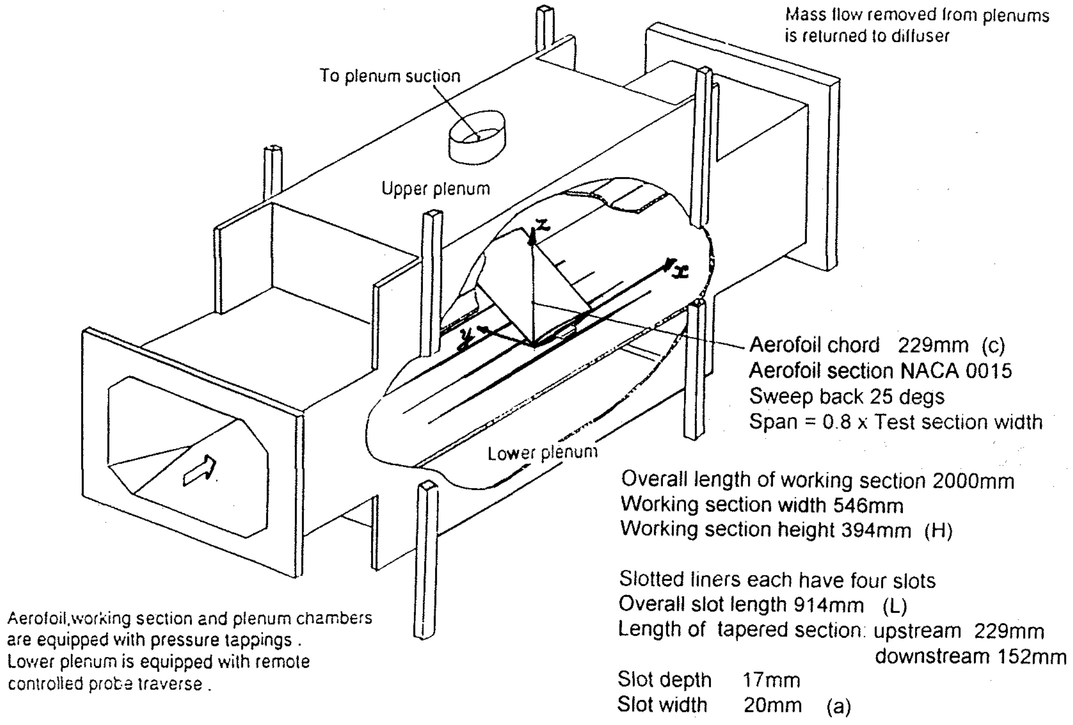

Aerofoil chord 229mm (c)
Aerofoil section NACA 0015
Sweep back 25 degs
Span = 0.8 x Test section width

Overall length of working section 2000mm
Working section width 546mm
Working section height 394mm (H)

Slotted liners each have four slots
Overall slot length 914mm (L)
Length of tapered section: upstream 229mm
downstream 152mm
Slot depth 17mm
Slot width 20mm (a)

Aerofoil,working section and plenum chambers are equipped with pressure tappings.
Lower plenum is equipped with remote controlled probe traverse.

Figure 1 Sketch of working section - slotted liners installed

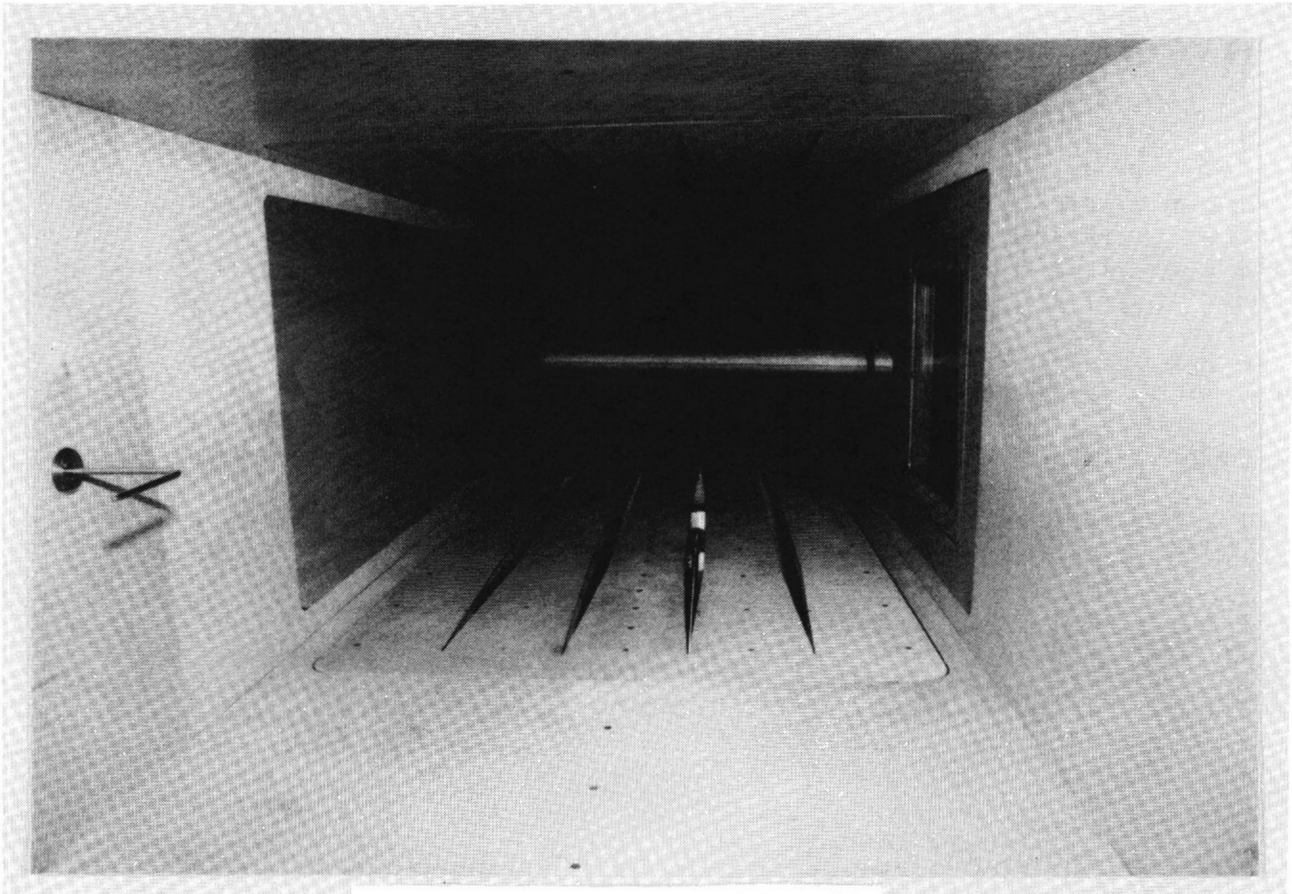

Figure 2 View of working section and wing model

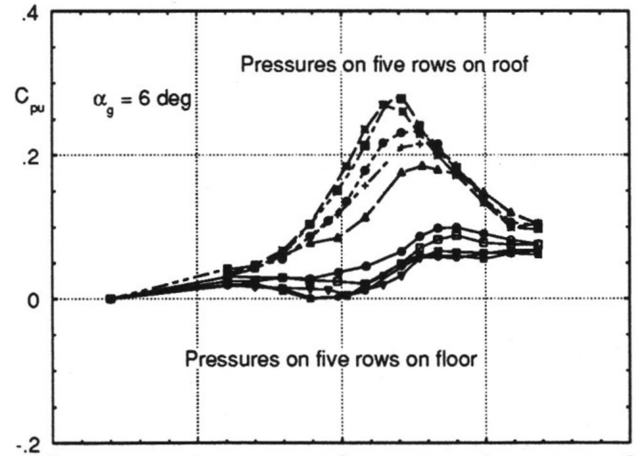

Figure 3 Roof and floor liner pressures, solid liners

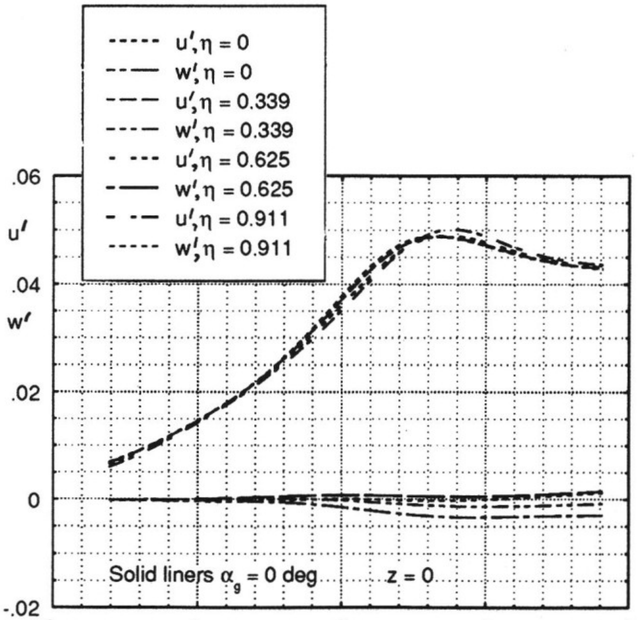

Figure 4(i) Interference velocities, solid liners, α_g = 0 deg

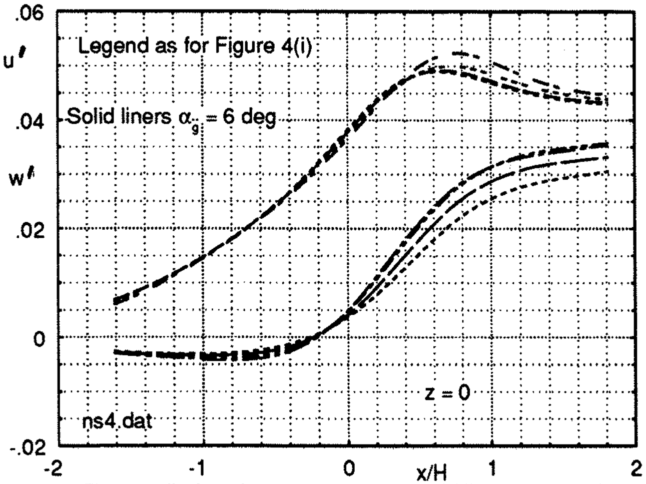

Figure 4(ii) Interference velocities, solid liners, $\alpha_g = 6$ deg

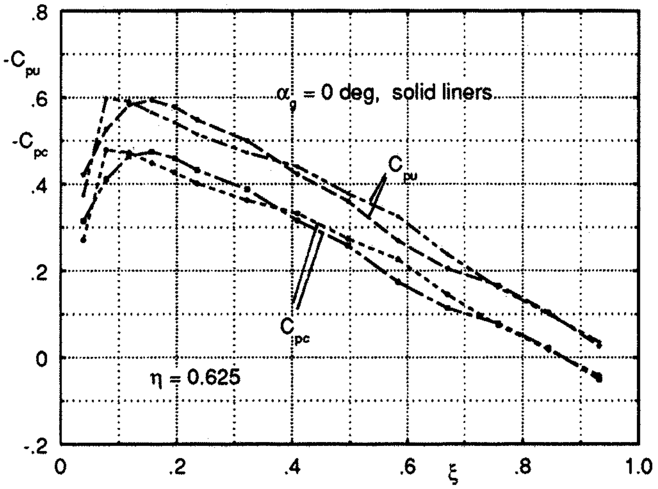

Figure 6 Pressure coefficients on middle row of wing tappings

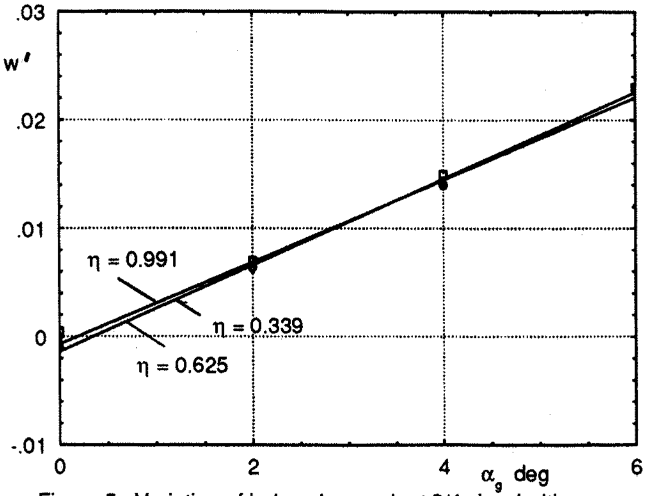

Figure 5 Variation of induced upwash at 3/4 chord with α_g

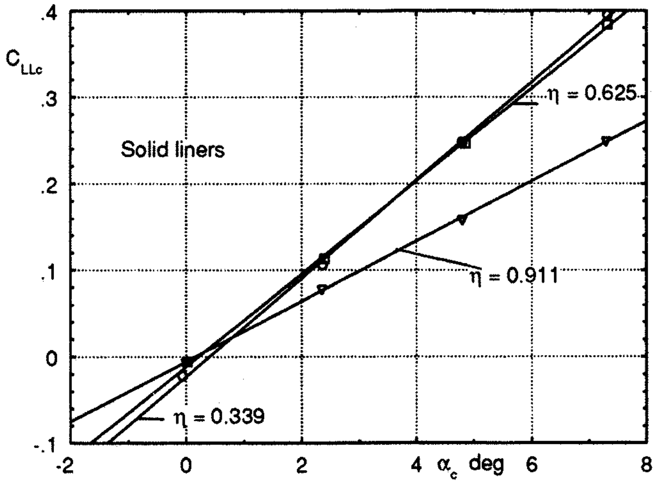

Figure 7 Variation of C_{LLc} with corrected incidence at local 3/4 chord

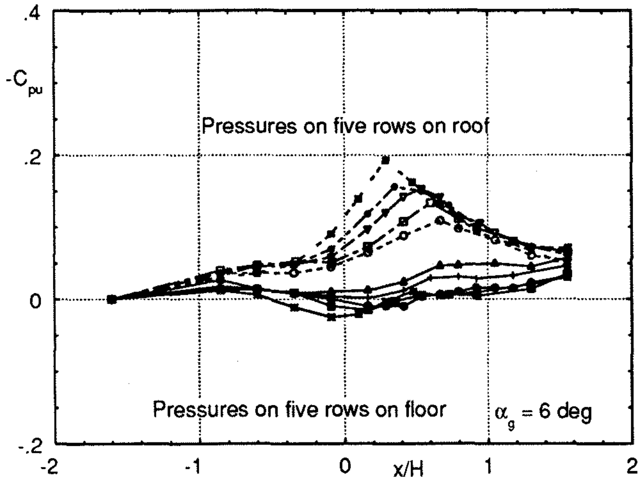

Figure 8(i) Roof and floor liner pressures, slotted liners

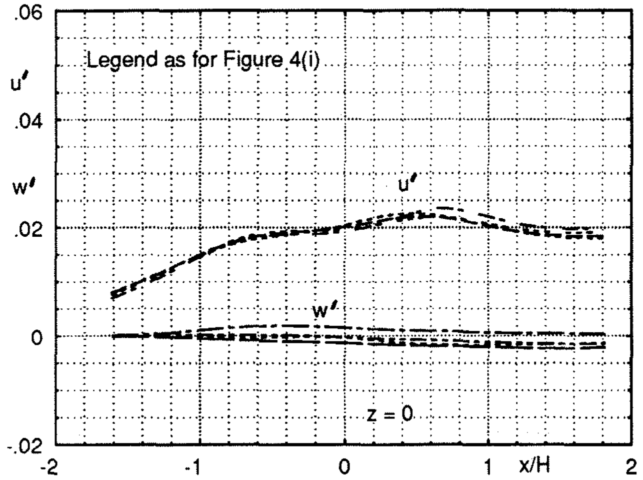

Figure 9(i) Interference velocities, slotted liners, $\alpha_g = 0$ deg

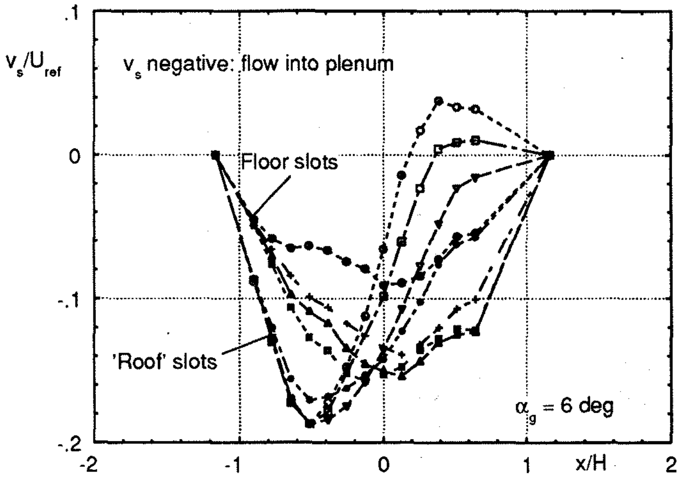

Figure 8(ii) Slot normal velocity distributions

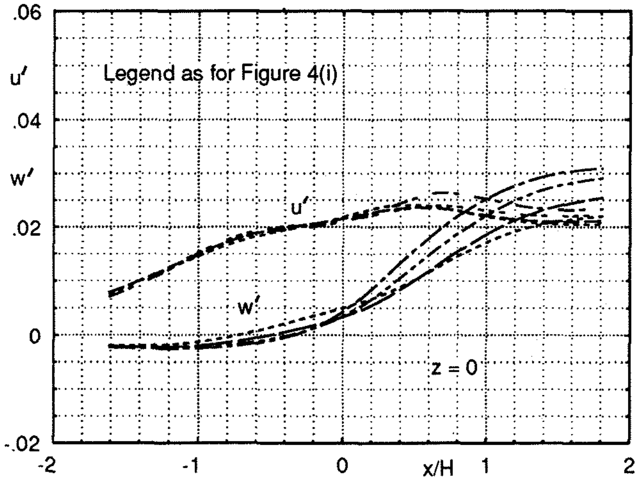

Figure 9(ii) Interference velocities, slotted liners, $\alpha_g = 6$ deg

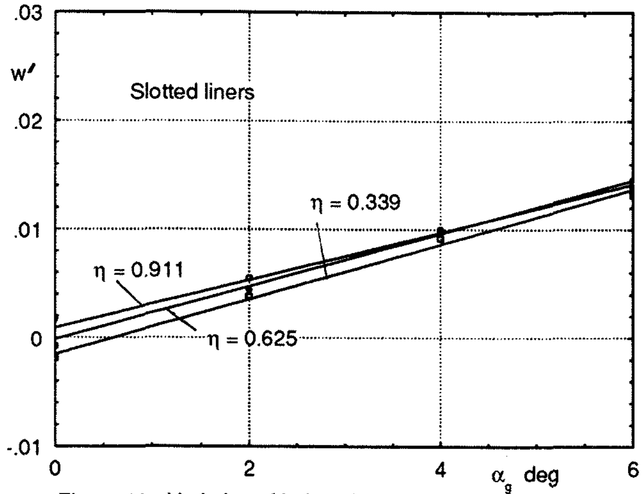

Figure 10 Variation of induced upwash at 3/4 chord with α_g

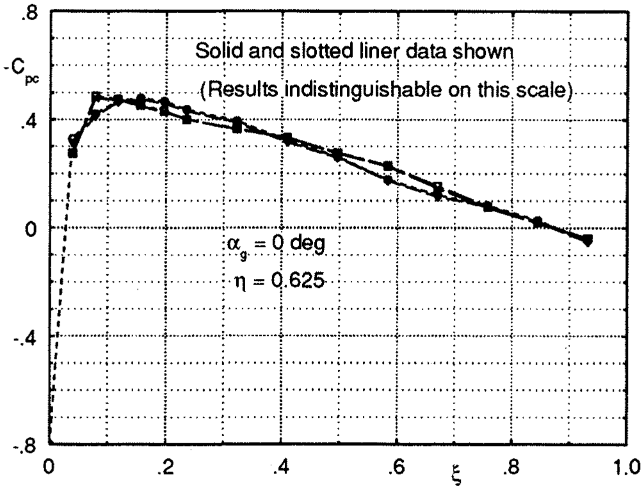

Figure 12(i) Corrected pressure coefficient distributions

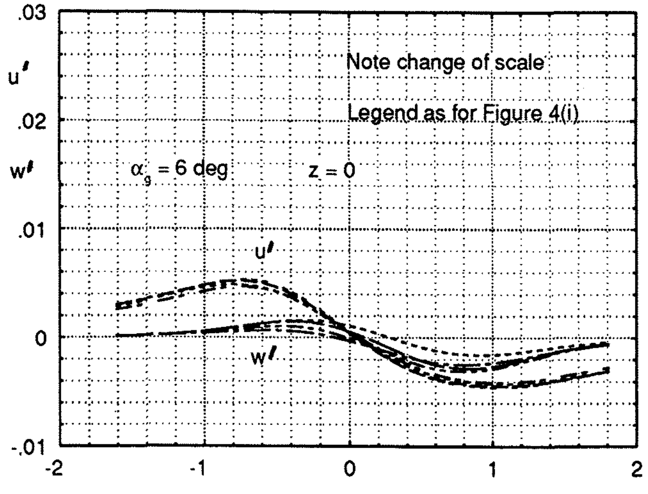

Figure 11 Direct contribution of slot normal velocity to interference

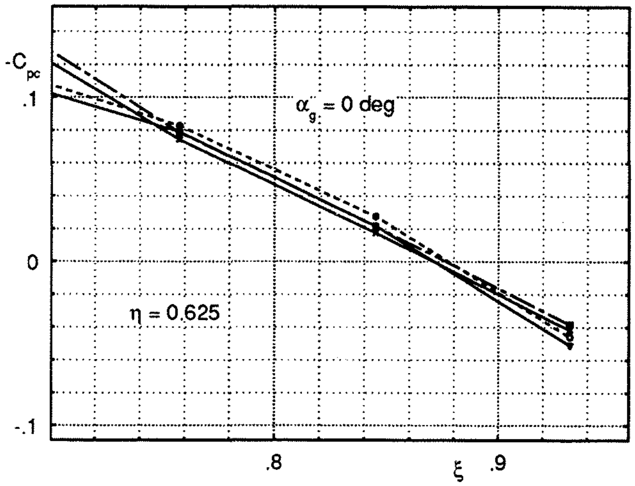

Figure 12(ii) Corrected pressure coefficients - expanded scale

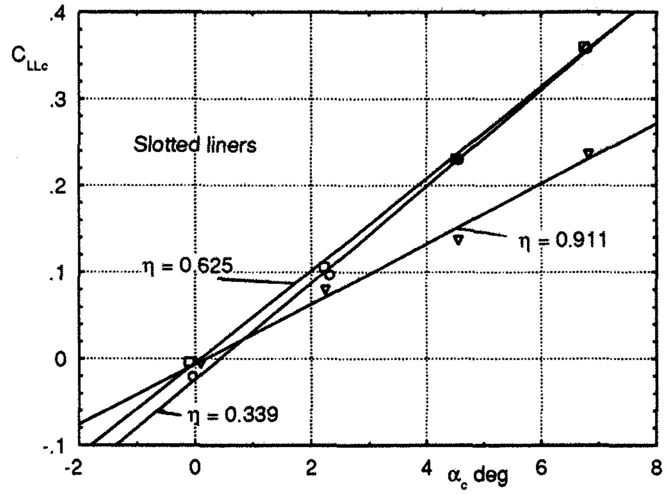

Figure 13 Variation of C_{LLc} with corrected incidence at local 3/4 chord