AN EXPERIMENTAL INVESTIGATION INTO THE RATIONALE OF THE APPLICATION OF WIND TUNNEL WALL CORRECTIONS

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Abstract

Correcting wind tunnel data for the effects of gradients of interference induced by the walls of the test section is not straightforward. The object of this work was to gain insight into the necessary corrections by studying the effects of wall interference gradients on the aerodynamic performance of two-dimensional aerofoil sections. The experimental work was performed in test sections employing adaptive flexible walls, although the findings are applicable to any type of wind tunnel. The unique ability of adaptive flexible wall test sections to actively manipulate and control, rather than simply minimise, wall interference was used to deliberately introduce known streamwise gradients of wall-induced upwash into the test flowfield. Model performance was derived from the measurement of pressure distribution. The ¾ chord theorem which yields an incidence correction to the lift curve in the presence of a linear upwash gradient has been extended to cover non-linear gradients, and to permit a similar correction in connection with pitching moment. The analysis has also been used to predict the aerofoil loading due to a given upwash gradient. The correction theorems are generally well supported by the experiments but there is only rough agreement between the predicted and experimental load distributions.

Symbols

A	coefficients in equation 1
c	aerofoil chord
C_p	pressure coefficient
C_L	lift coefficient
C_m	pitching moment coefficient about leading edge
M	Mach number
q	angular pitch rate
x	distance downstream of leading edge of model
x_P	chordwise location of point where wall-induced upwash determines a correction to α for given C_L
x_M	chordwise location of point where wall-induced upwash determines a correction to α for given C_m
u	streamwise component of wall-induced velocity perturbation on centreline of test section
U	reference airspeed
w	vertical component of wall-induced velocity perturbation on centreline of test section
α	incidence
β	Prandtl-Glauert factor, $\sqrt{(1-M^2)}$
$\delta\alpha_n$	incidence correction to lift coefficient for a non-linear upwash gradient
θ	alternative coordinate, $\cos^{-1}(1-2x/c)$

Introduction

When correcting wind tunnel data for the effects of interference induced by the walls of the test section it has become normal practice to apply a global correction to Mach number and incidence. These corrections are usually referred to as the "primary corrections". In most cases (particularly in conventional closed test sections) there remains the need to apply further corrections because the wall interference is not distributed evenly over the model i.e. there are gradients of wall interference. Such corrections may be referred to as the "secondary corrections" but are not usually applied in general wind tunnel testing.

This investigation was designed to yield information on the nature and magnitudes of some of the necessary secondary corrections. The broad rationale was to expose a model, of known interference-free performance, to gradients of wall interference and to monitor their effects on the model performance. The intention was the experience gained would lead to a better understanding of the effects of wall interference and permit estimates of the secondary corrections to be made for application in general wind tunnel testing.

The experimental work was confined to tests on two aerofoil sections in test sections comprising two adaptive flexible walls with two rigid sidewalls supporting the model. This paper is therefore restricted to two-dimensional flows. The unique ability of adaptive flexible wall test sections to actively manipulate and control, rather than simply minimise, wall interference was exploited to deliberately introduce known streamwise gradients of wall-induced upwash into the test flowfield. Model performance was derived from the measurement of pressure distribution, which precluded any meaningful study of model drag. While the wall interferences of interest include those due to gradients in blockage and upwash, this paper concentrates on the issue of gradients in wall-induced upwash. Some effects of blockage gradients have been published elsewhere[1-4].

The experiments were supported by analytic work extending the ¾ chord theorem of Pistolesi[5], which is relevant to the influence of a uniform streamwise gradient of upwash on lift. This has been extended analytically to encompass the general case of non-linearity in wall-induced upwash. During the analysis of wind tunnel data a certain pattern became apparent in the variations of pitching moment. This led to further analytic work which allows predictions of the influence of non-linear gradients of wall-induced upwash on pitching moment. The analytic work also includes a prediction of the aerofoil loading due to a given upwash gradient. Although the experiments were performed in adaptive flexible wall test sections the findings and conclusions are general and therefore applicable to any type of wind tunnel.

Background

The experiments in connection with this study involved the testing of two-dimensional aerofoil sections in test sections employing two adaptive flexible walls. Normally the aim of such test sections is to shape the two flexible walls so that their interference is eliminated in order to simulate the flow around the model in an infinite flowfield, so-called free-air flow.

In this work the aim is somewhat different in that the objective was to modify the test environment in a controlled way by introducing wall-induced velocity perturbations which are of use in determining aerodynamic performance other than that of just steady flow past the model in an infinite region. While the general notion is not new it has been significantly extended in scope during the course of this investigation.

Before presenting some relevant background to the investigation two points relating to the nature of flexible adaptive walls should be emphasised. Firstly, despite the flexibility of the walls and therefore the broad range of possible shapes which can be selected, it is a mistake to view this freedom as a source of uncertainty over conditions in the test section, including the angle of incidence. A second and in fact related point is that as the boundary conditions introduced by the two impervious flexible walls are rather well known in terms of pressure distribution, shape and therefore slope, their interferences can be quantified with some certainty.

There are at least four past experiments at Southampton University where adaptive flexible walls have, intentionally, not eliminated wall interference. The list is not exhaustive partly because it is confined to examples of two-dimensional flow:

(i) *Ground effect.* The flexible wall over the top of the model is streamlined in the usual way. The lower wall remains straight in order to introduce components of velocity perturbation appropriate to ground proximity[6].

(ii) *Cascade of identical models.* In one embodiment of this notion the flexible walls are placed one pitch apart either side of a model of a single blade and then set to identical contours simulating the interferences of adjacent models. The blade (more if desired) together with the flexible walls simulate a lifting cascade of untwisted blades[6-8].

(iii) *Open or closed test sections.* In these simulations the flexible walls are adjusted to introduce the appropriate boundary conditions with their associated interferences[6,9]. In the former case the walls are contoured to give a constant pressure along their lengths equal to the reference static pressure. For the latter they are notionally straight. In each case both flexible walls introduce interference velocity perturbations, but of different signs.

(iv) *Steady pitching.* The nature of the controlled interference in this case is a flow curvature, created by the collective action of the pair of flexible walls[10]. The tests were designed to yield two of the pitch rate derivatives dC/dq, where C is an aerodynamic coefficient and q is rate of pitch. With the model installed in the test section the flexible walls were first streamlined for zero free-air interference. Then the walls had arcs superimposed, centred below the test section, resulting in the simulation of negative pitch rate at steady airspeed.

Some interesting points should be made before leaving these early examples of alternatives to streamlining for free-air conditions.

The first relates to the closed test section of case (iii) above. Wall-induced velocity perturbations nominally along the chord of a high blockage aerofoil section in a straight closed test section are shown on figure 1. The wall interference is split into orthogonal components, u representing the streamwise component of perturbation and w the vertical component: commonly called blockage and upwash respectively. These have been made non-dimensional with respect to the reference airspeed U. The distribution of u or w over the model can be viewed as comprising a mean level coupled with a varying, non-linear component. The former are used in classical correction methods to derive the primary corrections[11,12] to Mach number and incidence. The latter, the "residual variations", are often disregarded but can be worryingly prominent in tests on large models in conventional closed walled tunnels and for smaller models at high subsonic speeds in the same type of tunnel. The situation is further complicated because normally there are variations of wall interference in the vertical direction[13,14].

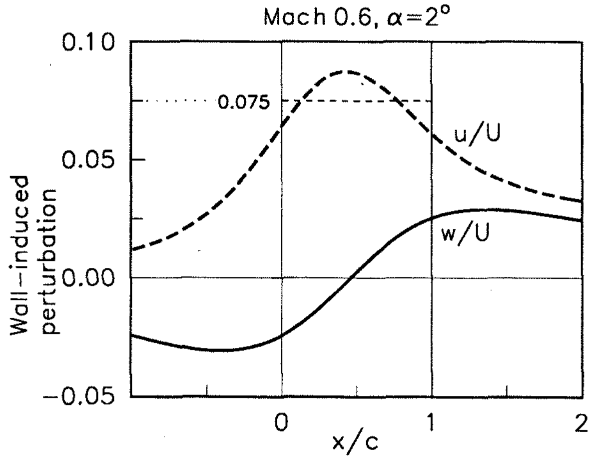

Figure 1. Chordwise wall-induced upwash and blockage, NPL-9510 section, straight impervious walls.

In the rather extreme example (solid blockage≈11%) of figure 1, the mean level of wall-induced blockage might be taken as about 7½% of the reference airspeed as indicated, which would constitute a primary correction. However across the chord there is a strongly non-linear residual variation of blockage inside a band of about ±1% about the mean for which a separate secondary, but not insignificant, correction should be made. The wall-induced upwash appears to be dominated by residual variation no matter what location is selected along the chord for choosing the value of the primary correction.

Adaptive flexible walls may be used to remove just the varying portion of the wall-induced velocity, in which case the data are adjusted in a simple manner just for the primary interference. Or, and more commonly, the adaptive walls may be used to remove all wall interference so that the data need not be corrected. As already stated, in this study the opportunity was taken to exploit our control over interference, control which is perhaps uniquely provided by adaptive flexible walls, to introduce known measures of residual interference in order to reveal their impact on the performance of the model.

This leads to a point related to case (iv) above. This test can be viewed in a different light. Instead of regarding the test as one simulating steady pitching, the same experiment may be viewed as simulating a steady-state test on a model of modified camber. This approach was exploited during the course of this investigation. The adaptive flexible walls were used to generate controlled gradients of wall-induced upwash, linear and non-linear, effectively introducing various forms of camber. This allowed the effects of the gradients to be examined in terms of changes of pressure distribution on the model.

The nature of the experimental work is illustrated in figure 2. Sketch 2(a) represents an aerofoil model in an adaptive test section simulating free-air flow. For simplicity the model is represented by a notional uncambered chordline aligned with the flow and the shapes of the top and bottom walls are not shown. Once the flexible walls have been streamlined the test section is curved following an arc, centred above the test section over the mid-chord point in the case depicted by sketch 2(b). The curvature in the flow so introduced creates a downwash over the leading half of the aerofoil, a wall-induced downwash, and the opposite over the rear half. The distribution of wall-induced upwash is also illustrated on figure 2, an approximately linear variation for large radii in relation to the chord.

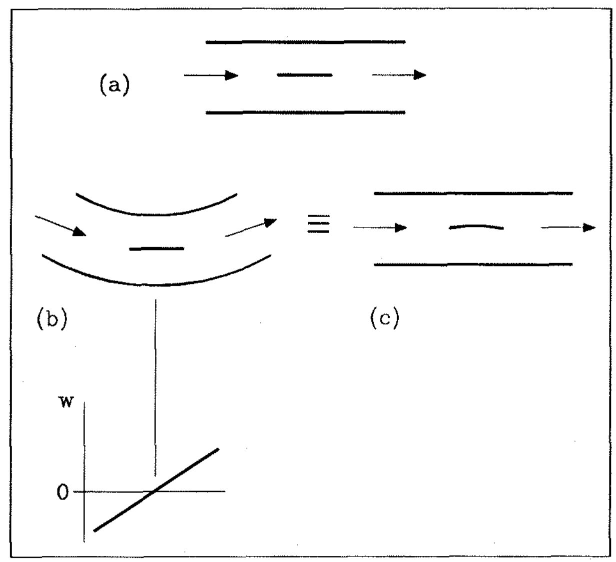

Figure 2. A schematic illustrating the use of adaptive walls to induce a gradient of wall-induced upwash in the test flowfield.

In order to anticipate changes of aerodynamic performance it is convenient to view the experiment depicted by sketch 2(b) as equivalent to sketch 2(c) where the test section curvature has been removed leaving the aerofoil effectively with positive camber (or more positive camber if the section had been initially cambered). The expectation would be for lift to increase, also the nose-down pitching moment about any forward point.

Experimental Details

Low Speed Tests

The low speed adaptive wall test section (SSWT) was nominally 6 inches deep[10]. In these experiments, outlined under (iv) above, the curvature was centred under the test section, thus simulating the effects of negative camber. At the time of these tests no wall-interference assessment method was available. The aerofoil section was NACA 0012-64 of 5.4 inch chord. The model had been tested by NASA in the Low Turbulence Pressure Tunnel (LTPT) at Langley Field in 1974 in support of our work on adaptive wall test sections, with transition strips, Reynolds and Mach numbers identical to those to be used later in SSWT which were 314,000 and 0.105 respectively. The depth of LTPT, 90 inches, was such that the data was viewed as being free from top and bottom wall interference.

Transonic Tests

The section tested in the transonic range (Mach 0.6, 0.7) was NPL 9510 of chord equal to the nominal depth of the test section, 6 inches. In order to include any coupling that might exist between wall interference and transition no attempt was made to fix transition. Details of the tunnel, (TSWT), and model have been well reported[1-4,13,14]. The chord Reynolds number in the tests reported in this paper was order 2 millions. In separate experiments on a thin section at zero incidence the transition Reynolds number was approximately 1.05 million.

When they were being used to induce camber the flexible walls were simultaneously adjusted to eliminate any residual wall-induced blockage along the test section centreline. The residual interferences and more importantly the imposed gradients of upwash were calculated from wall contour and wall pressure data using the method of Ashill and Weeks[15] modified for the case of two curved walls[16]. The effects of any compliancy of the flexible wall boundary layers was included in the wall interference assessment by calculating changes of displacement thickness according to the Lag-Entrainment method[17]. In these tests the curvature was centred over the test section in the manner of figure 2, thus simulating the effects of positive camber.

The effects on lift

For the case where a gradient of upwash varies linearly across the chord Pistolesi showed that the effect of the change of lift induced by the effective camber could be taken into account by correcting the incidence according to the upwash existing at the ¾ chord point. Data taken on NPL 9510 in TSWT have been corrected in this manner[13,14]. There was general agreement between various sources of lift curve data, that is reference data from NPL[18], lift measured in TSWT by sweeping incidence while streamlining the flexible walls, and separately in TSWT at fixed incidence while inducing camber with the flexible walls. The latter is called a camber sweep because the effective incidence is varied, without change of actual incidence, by introducing varying levels of wall-induced upwash and thus camber. The agreement supported the use of Pistolesi's theorem in connection with lift as a means for correcting incidence for the effects of gradient of upwash. It also appeared, perhaps surprisingly, that the theorem could be applied to transonic flows (or at least to the transonic flows studied)[13,14] as well as to flows that satisfy the restrictions of the linear theory by which it was derived.

Although it was not the general intention, it happened that in most of the cases in TSWT, where the walls had been used to induce gradients of upwash, the gradients had exhibited some degree of non-linearity. The linearity could be improved by further wall adaptation but this was demonstrated in only two tests[13,14]. It was therefore a little surprising that the C_L-α agreement was fairly good. However it should be noted that in conventional wind tunnel tests non-linear components of upwash gradient are normally present. Figure 1 is an example. The principal weakness in the camber-derived data was some scatter at the higher incidences which, it was suggested, might have been due to the Mach numbers at the walls rising to levels very close to sonic where the method of assessing wall interference could become rather too approximate.

The question of the influence of non-linearity of the chordwise variation of wall-induced upwash has been resolved by the following extension to the Pistolesi theory.

According to linearised aerofoil theory[19] corrected to allow for compressibility[20] the incremental loading due to a chordwise distribution of wall-induced upwash w is given by:

$$\Delta(\delta C_p) = 4\left(A_o \cot\frac{1}{2}\theta + \Sigma_1^\infty A_n \sin n\theta\right) \quad (1)$$

here

$$A_o = \frac{1}{\pi\beta}\int_o^\pi \frac{w}{U}d\theta \quad (2)$$

$$A_n = -\frac{2}{\pi\beta}\int_o^\pi \frac{w}{U}\cos n\theta d\theta \quad (3)$$

where $\theta = \cos^{-1}(1-2x/c)$.

Integration of the incremental loading given by equation (1) along the chord gives the incremental lift coefficient

$$\Delta C_L = 2\pi\left[A_o + \frac{1}{2}A_1\right] \qquad (4)$$

Referring to equations (2) and (3) it is possible to rewrite equation (4) as

$$\Delta C_L = 2\pi\frac{w(x_P)}{\beta U}$$

where

$$\frac{w}{U}(x_P) = \frac{1}{\pi}\int_0^{\pi}\frac{w}{U}(1-\cos\theta)\,d\theta \qquad (5)$$

It is readily shown that x_P=3c/4 for a wall-induced upwash that varies linearly with x along the aerofoil chord. This implies that the appropriate point for applying the correction to angle of incidence is the ¾ chord point for this type of distribution of wall-induced upwash. This is the well known ¾ chord theorem first proposed in 1933 by Pistolesi[5]. For quasi-linear variations it may be expected that the point P will be close to ¾ chord.

The C_L-α camber sweep data of figure 13 in reference 8 has been re-analysed, with the correction to incidence now derived from equation (5). The wall-induced upwash distribution w/U involved in the integration is derived while quantifying wall interference, a standard procedure in TSWT. All of the data were obtained with a positive slope dw/dx which, as has been seen, induces positive camber.

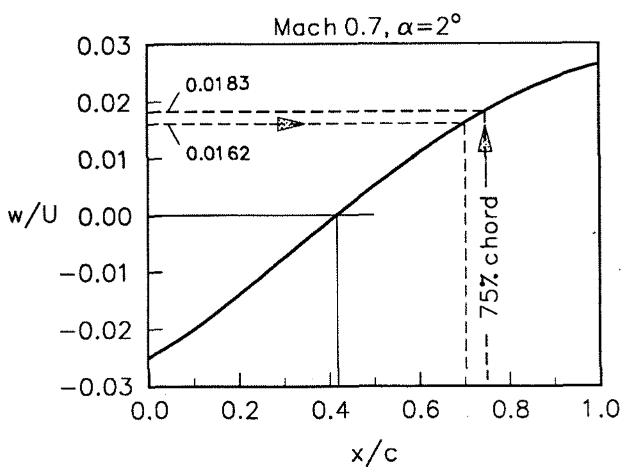

Figure 3. An example of an wall-induced upwash gradient.

Figure 3 is one example of the variation of wall-induced upwash in a test on NPL 9510 in TSWT at Mach 0.7, one of the more non-linear gradients experienced. Zero induced upwash is seen to be at about 42% chord which may be interpreted to mean that the induced camber is centred near the middle of the section, with the leading and trailing edges drooped from the camber. The lift is raised by this effect and Pistolesi's theorem provides one estimate of the necessary correction to incidence. Highlighted is the linear-gradient Pistolesi point (75% chord) and the corresponding incidence correction Δα (0.0183 radians, 1.054°). The incidence correction according to the recently derived analysis for non-linear gradients (equation (5)) is $\Delta\alpha_n$= w/U(x_P)=0.0162, 0.929°. The intercept of this angle with the upwash curve shows that the incidence correction is the wall-induced upwash at about 70% chord. The error incurred by adopting Pistolesi's original analysis is about 0.12°.

To permit a comparison of data reduction using linear and non-linear gradient analysis, all sets of data, that is the reference NPL α-sweep, TSWT α-sweep with streamlined walls and the TSWT camber-sweep at constant values of α, the latter analysed using the Pistolesi point (¾ chord) and equation (5), are shown on figures 4(a) and 4(b) for tests at Mach 0.6 and 0.7 respectively.

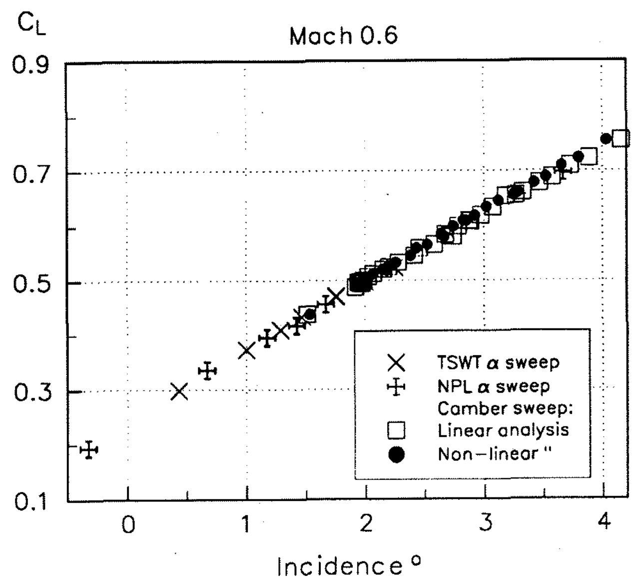

Figure 4(a). A comparison between reference data, and camber-sweep data analysed by methods for linear and non-linear gradients. Mach 0.6.

The Mach 0.6 camber-sweep data was taken at the two incidences of 2° and 3°. It is interesting to note that the band of corrected values of incidence induced by camber, with the model set at 2°, varied from 1.5° to 3.2°. The principal effects of invoking the new non-linear analysis are that the scatter in this data is reduced somewhat and that linear analysis can evidently involve an incidence error of up to order 0.1° under the conditions of these tests. Along with the reduced scatter is a systematic change, a slight steepening of the lift curve slope.

The camber-sweep data of figure 4(b) was taken at 2° incidence. Examination of that data shows that the effective incidence was changed through the range +0.9° to -0.2° according to equation (5). The range of induced C_L was correspondingly substantial: this varied through a range of about 0.24. Adopting the non-linear analysis has again shifted the lift curve slope to a slightly higher value while leaving it generally in good agreement with the reference data. Also the scatter which was very evident at the higher induced-camber conditions has been reduced by a useful amount although some improvement remains desirable.

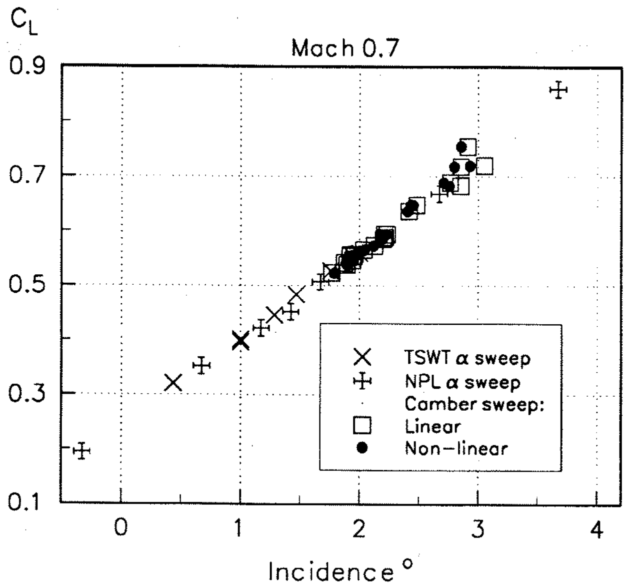

Figure 4(b) A comparison between reference data, and camber-sweep data analysed by methods for linear and non-linear gradients. Mach 0.7.

A general conclusion to be derived from this experience is that corrections can be made for the effects of gradient in wall-induced upwash to the particular global measure of performance C_L. As non-linear gradients are possible, in those cases when the necessary information on the gradients is available the best method of correction might be by means of the newly derived analysis applying to non-linear gradients because it is simple to implement. Although the analysis is based on classical linear theory the evidence to date suggests that it may be applied to transonic flows.

Aerofoil loading

The change of lift coefficient induced by wall interference is proportional to the incidence induced at approximately the 3/4 chord point, as we have seen. The induced incidence at this point varies with the induced flow curvature and therefore camber, and on where it is centred along the chord. The point is illustrated by the sketches on Figure 5. In each sketch the magnitude of the induced camber is the same. In sketch 5(a) the point of zero wall-induced upwash, and therefore camber, is centred at ¾ chord as indicated by the arrow x. At this point the tangent to the induced camber line is aligned with the free stream and therefore we would expect almost no change in C_L compared with the same incidence in the absence of induced camber. However in (b) the induced upwash is centred at x at about the quarter-chord point: the induced incidence at the ¾ chord point and the increment of lift would each be substantial. Therefore the magnitude of the wall-induced flow curvature, and the point at which it is centred, each have an impact on C_L and effective α.

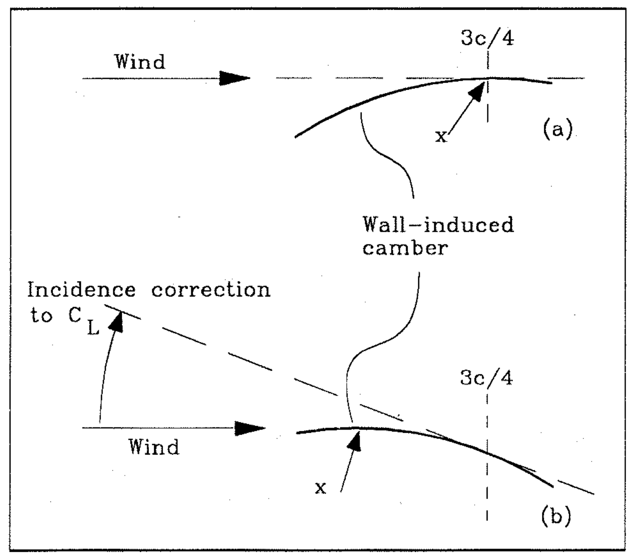

Figure 5. A schematic illustrating the effects on induced incidence of camber and where it is centred.

In the case depicted by figure 5(a), upwash centred at about the Pistolesi point (¾ chord), we should expect changes in the load distribution but little in the total lift.

One source of information on the change in local loading is equation (1) where the coefficients A are available from integrations of experimental data. The first 5 terms in the infinite series were used in the evaluation of $\Delta(\delta C_p)$ and the results of a few typical cases are plotted on figures 6. In each case there is a "% chord" marked. This is the position along the chord where the gradient of upwash was centred. On figure 6(a) one pair of curves applies to an experiment at Mach 0.6 with upwash centred at 76%, very close to the Pistolesi point. The distribution derived from equation (1) is the broken line. The data points are derived from aerofoil surface pressure measurements.

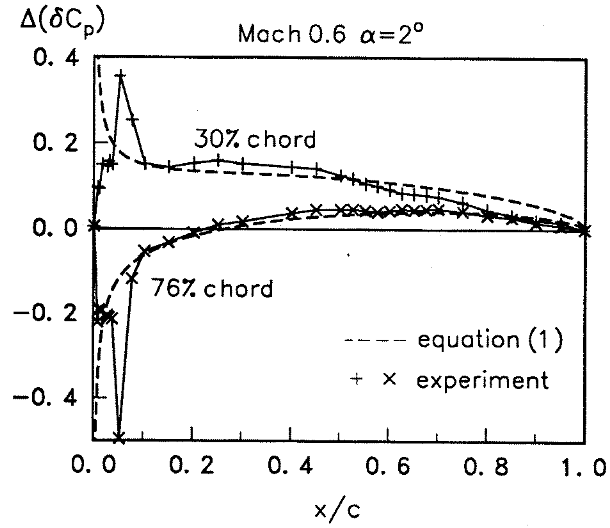

Figure 6(a). Examples of change of loading with centre of wall-induced camber. NPL 9510 section, Mach 0.6.

There is only rough agreement between the distributions in detail. The abrupt reduction of loading experienced at 10% chord is due to the upper-surface shock advancing over that orifice as a result of the effective drooping of the leading edge in the manner sketched in figure 5(a). However both sources of load distribution, that is equation (1) and pressure measurements, lead to good estimates of total lift. Additional load over the rear 75% of the section is balanced by reduced load forward. For example C_L was 0.4992 compared with 0.5005 with streamlined walls.

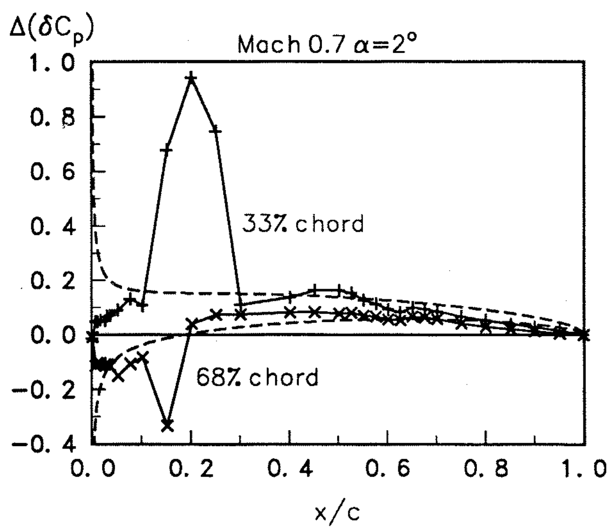

Figure 6(b). Examples of change of loading with centre of wall-induced camber. NPL 9510 section, Mach 0.7.

In contrast, the loading curves with upwash centred at 30% chord, somewhat like figure 5(b), show loading increased everywhere but again with significant detail differences between the predictions of equation (1) and experimental measurements. In this case the wall-induced upwash increases C_L substantially, by 0.1087. The increment predicted with equation (4), with the values of coefficients A_0 and A_1 determined from experimental data, was 0.1166. Considering the significant detailed differences in loading this is quite reasonable agreement. This suggests that it might be possible to correct C_L and C_m for a given single incidence as opposed to the procedure followed in this paper in which incidence is corrected differently for each coefficient.

These trends are repeated in the Mach 0.7 data of figure 6(b). Notable in the experimental data with upwash centred at 33% chord is the consequence of a marked aft movement of the upper surface shock, traversing 3 orifices and more than 10% of the chord.

Effects on pitching moment

Pitching moment was derived from pressure distributions and referenced to the leading edge. Tests in TSWT pointed to somewhere near to the rear of the aerofoil as a reference point where upwash should be evaluated when correcting incidence in presenting pitching moment data.

Some of the evidence is on figure 7 which shows pitching moment as a function of the change of wall-induced upwash over the chord of the section. The numbers alongside the data points are the positions along the chord where the induced camber was centred for that test, in % chord. A pattern exists: high percentages towards the top of the plot.

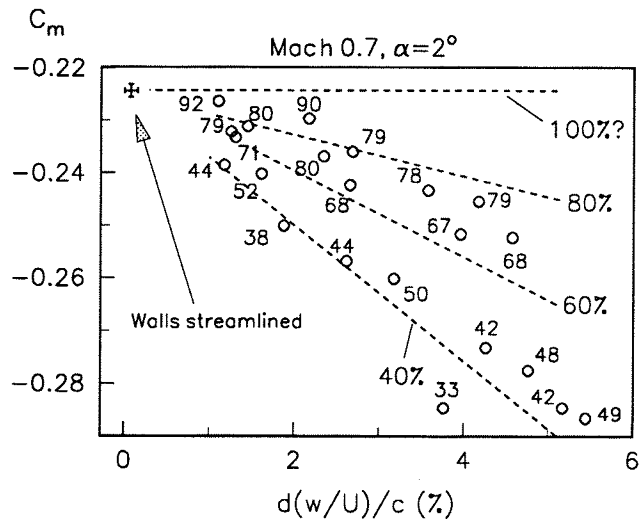

Fig 7. Accumulated C_m data on section NPL 9510 in the presence of a gradient in wall-induced upwash.

The maximum value of wall-induced camber shown on figure 7 is about 3.12°; wall movement limitations in TSWT prevented the imposition of larger cambers. It is interesting to note that Steinle and Stanewski[21] recommends a flow curvature of less than 0.03° per chord. It is generally accepted that such a requirement is usually not satisfied in test sections with solid walls and may not be in some porous-wall wind tunnels. Nonetheless, it can be safely stated that all upwash gradients imposed in the course of this investigation are extremely large by conventional standards. Careful examination of figure 7 will show that d(w/U)/c is not quite zero for the streamlined walls point. The value was 0.072%, 0.04°.

Superimposed on figure 7 are broken lines positioned approximately along lines of constant percentage. The suggestion is that induced camber centred at approximately the trailing edge does not change the pitching moment, in contrast with the nominal 75% chord point for lift. Data at Mach 0.6 suggested the same finding[3]. This prompted a search for theoretical backing, which yielded the following.

In accordance with the earlier analysis, the incremental pitching moment coefficient about the leading edge, nose up positive, may also be found by integrating the moment of the loading to give:

$$\Delta C_m = -\frac{\pi}{2}\left(A_0 + A_1 - \frac{1}{2}A_2\right)$$

this may be expressed as:

$$\Delta C_m = -\frac{\pi}{2\beta}\frac{w(x_M)}{U}$$

where

$$\frac{w(x_M)}{U} = \frac{1}{\pi}\int_0^{\pi}\frac{w}{U}(1-2\cos\theta+\cos 2\theta)\,d\theta \qquad (6)$$

an equation applicable to linear and non-linear gradients. It may be verified that x_M=c for a wall induced upwash that varies linearly with chordwise position. In other words the appropriate point for making the correction to angle of incidence on plots of pitching moment against angle of incidence is the trailing edge, for linear variations of wall-induced upwash.

That the point M is further downstream than the point P for linear variations of induced upwash comes about because the function multiplying the induced upwash in the integrands of equations (5) and (6) is much more weighted towards the trailing edge for the pitching moment integral than for the lift integral. This is illustrated in the sketch on figure 8.

There is some experimental support for these conclusions in figure 7, but additional evidence was sought from further analysis of experimental data.

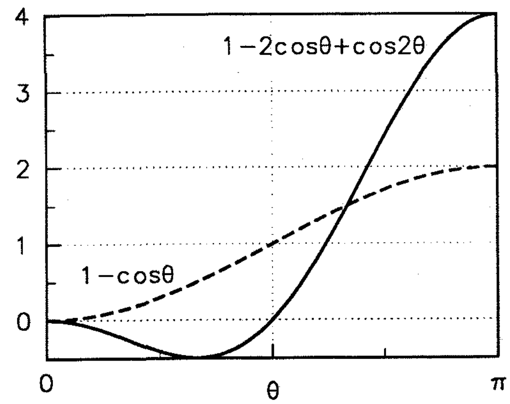

Figure 8. Functions in the integrands of equations (5) and (6).

Low speed tests

These experiments, originally designed for stability-derivative measurement[10] were performed in SSWT in a manner which allowed evidence to be extracted in support of the above. The essentials have been summarised. Representative wall contours are shown on figure 9 for a test at 6° incidence. The flow is left to right, LE and TE mark the leading and trailing edges. The radius of curvature, centred below the test section, was 200" to the tunnel centreline.

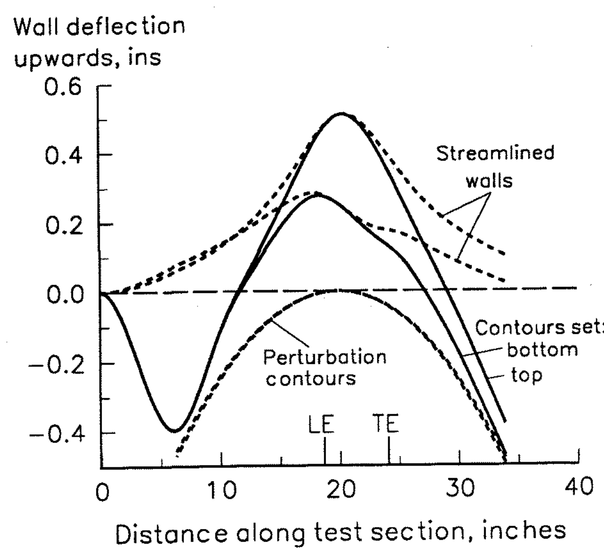

Figure 9. Typical streamlined wall contours and their perturbations inducing negative camber in low speed tests in SSWT.

Wall interference assessment was not available in these tests. If however the wall-induced flow angularity is assumed to follow the perturbation contours then the gradient of wall-induced upwash may be determined. Following this assumption the results have been reduced using upwash at the trailing edge to determine the correction for incidence, i.e. the upwash gradient was assumed linear. The reduced data is shown on figure 10 with a reference line which is the C_m-α slope from the LTPT tests.

There is fair agreement between the two sources of data despite the assumptions which have been made and therefore the experiment supports the use of the upwash at, or near to, 100% chord for pitching moment incidence corrections for upwash gradients.

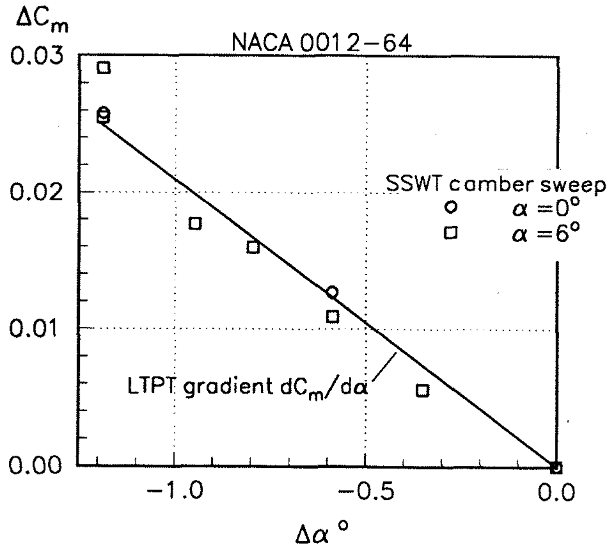

Figure 10. Change of pitching moment coefficient with change of effective incidence due to wall-induced camber.

Transonic tests

It was found that the differences between data analysed assuming an incidence correction equal to the wall-induced upwash at the trailing edge and equation (6) are small. Therefore only the latter camber-sweep data is shown on figure 11 together with C_m-α data also obtained in TSWT in an incidence sweep using streamlined walls. There is no NPL reference data available.

There is only a little overlap between the two data sets at each Mach number to help support a claim for agreement between the two experimental methods and therefore for the method of correcting C_m in general wind tunnel testing. This was an unfortunate consequence of mechanical restrictions on wall movement associated with the testing. Nevertheless, encouragement can be gained from the fact that the application of the correction method has succeeded in correlating quite well the broad bands of scatter exhibited by the C_m data on figure 7 and figure 54 of reference 3. Furthermore, the two sets of data for each Mach number at 2° incidence, that is one set taken under interference free conditions (streamlined walls) and a set taken in the presence of wall-induced upwash, seem to form parts of the same line and the trends are plausible.

Additional support may be inferred from the following point. The theory predicts a small correction to incidence when the wall-induced camber is centred near the trailing edge, even when the camber over the model is substantial. For example, on figure 7 near the 100% line there is a data point denoted by 90%: the number has been rounded and the gradient of upwash was in fact centred at 89.6% chord. For this test the wall-induced camber was 1.24° over the chord: the correction theories predict rather small incidence changes of about 0.15°.

The camber-sweep data at 3°, Mach 0.6, are out of alignment with the other data. The reasons for the discrepancy, in terms of incidence about ¼°, are not known. It is possible that at this angle of incidence transonic-flow effects may have an influence on correlation. Also there is the possibility that the absence of fixed transition has allowed movement of transition and effects on pressure distribution which are shown by pitching moment coefficient but not by lift coefficient.

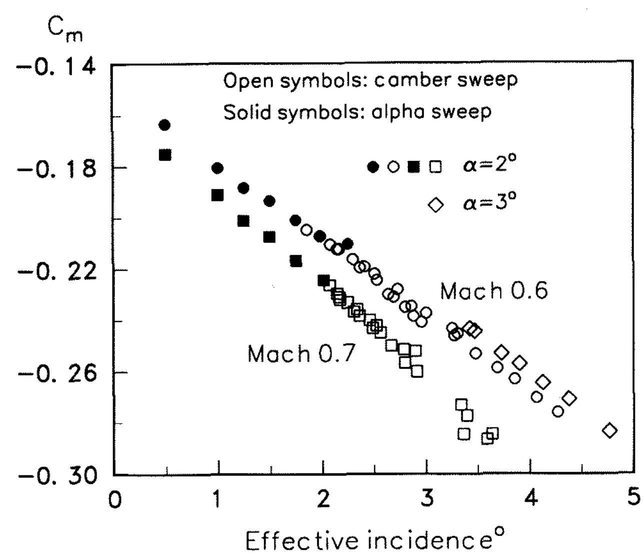

Fig 11. Curves of pitching moment coefficient against effective incidence derived from incidence and camber sweeps in TSWT.

Concluding remarks

The two-dimensional aerofoil tests have yielded experimental justification for methods of correcting two global aerodynamic coefficients, C_L and C_m, for the effects of wall-induced camber. Adaptive flexible wall test sections provided the means to generate the necessary upwash gradients, their effects being shown as changes in model surface pressure. The conclusions may be exploited in all wind tunnels where an assessment of wall interference is reasonably detailed.

This work has supported the use of the ¾ chord theorem to correct incidence at a given lift coefficient for the effects of a linear gradient of upwash. The theory was successfully extended to the more general case of non-linear gradients, involving the integration of experimentally-derived data to yield the incidence correction.

The theory was further extended to cover the pitching moment coefficient. In this case it was shown that the "equivalent Pistolesi point" was the trailing edge: for a linear upwash gradient the upwash at this point is the correction to incidence at a given value of pitching moment coefficient. An analytic method, again based on the integration of experimental data, was derived for application to non-linear gradients. Experimental support of this theory was encouraging but perhaps less conclusive than for lift.

The experience was that the differences between the correction methods, that is for linear and non-linear gradients, was small but significant. It is therefore concluded that in those circumstances where the wall interference assessment method yields information on non-linearity, the non-linear gradient method is preferable, bearing in mind its simplicity.

The methods which have been developed might help in deciding on the suitability of the design of a wind tunnel test. The order of magnitude of the effects of wall-induced upwash gradient can be estimated, indicating how far the conditions in a wind tunnel are from free air. A cautionary note must be raised however in connection with changes due to shock movement, on which the linear theory cannot provide guidance.

The range of two-dimensional experience needs extending to include a study of drag, to the effects of fixing transition, to other aerofoil sections in order to raise confidence by broadening the data base, to higher Mach numbers and perhaps to high lift. Furthermore, the existing data should be analysed to determine the potential for correcting C_L and C_m at a given incidence.

The effects of blockage gradients in two-dimensional flow need similar theoretical and experimental attention.

Finally there is the issue of extensions to three-dimensional models. For linear gradients of wall-induced upwash the principles described in this paper can be applied to wings of high aspect ratio by using the ¾ chord line and the trailing edge to determine the incidence correction associated with lift and pitching moment respectively. For arbitrary variations of wall-induced upwash over wings of small or moderate aspect ratio, it is suggested that use be made of the reverse-flow theorem as suggested by Taylor[12].

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Acknowledgements

This work was partly supported by the High Speed and Weapon Aerodynamics Department, DRA Bedford.