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ON THE USE OF SLOTTED WALLS IN TWO-DIMENSIONAL TESTING OF LOW-SPEED AIRFOILS

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Abstract

Experiments are described in which two-dimensional tests were made on 2 sets of 4 airfoils of the same profile but different chord at the same Reynolds number in a low speed wind tunnel with two interchangeable walls. Airfoils of one set had a fixed slot plus a slotted flap at 45°. Lift, drag and pitching moment were measured through a full incidence range for several longitudinally slotted wall configurations, and for solid walls. Some of these configurations were used for testing the second airfoil set, of the same profile without slot or slotted flap. Comparisons are made with existing theories, and it is concluded that the theories applicable to slotted walls are inadequate.

I. Introduction

The theory for corrections to wind tunnel data for the effects of wall constraints is well established for conventional tunnels, with solid walls, in which the models are small relative to the tunnel cross-sections, and develop only small lift coefficients. Current practice is well summarized in a report by Garner, Rogers, Acum and Maskell(1). Current research into the aerodynamics of STOL and VTOL aircraft configurations, however, requires testing at high lift coefficients, and often the use of relatively large models. If the corrections are still to be determined with satisfactory accuracy, at least one of the following criteria must be met - the theory for solid tunnel walls must be established for large models and high lift coefficients, much larger wind tunnels must be built, or a different type of tunnel wall configuration that reduces or eliminates the corrections must be developed.

Several very large wind tunnels for VSTOL testing have been built recently, but these cannot handle all the testing required, and the present investigation is intended to examine one aspect of the two alternatives to large tunnels mentioned above. When sectional characteristics of airfoils are required, it is usually desirable to test as large models as possible in order to obtain high Reynolds number N_R, and profiles with slots and flaps of current interest for STOL aircraft will develop high values of lift coefficient C_L. Under these conditions, wall corrections in the presence of solid walls become large enough that their accuracy as calculated by conventional theory is uncertain. On the other hand, the major corrections are of opposite sign for tests in an open jet wind tunnel, which raises the possibility of using partly open, partly solid walls to produce cancelling effects, and perhaps negligibly small resultant corrections.

A popular form of opening for such walls is a set of uniformly spaced narrow longitudinal slots, and in the present investigation the effects of different configurations of longitudinal slots are measured and compared with one another and with the effects of solid walls in two-dimensional testing of low-speed airfoils.

II. Experiments

The measurements were made in the low speed wind tunnel of the Mechanical Engineering Department of the University of British Columbia. This tunnel has a test section of 36 in. by 27 in. over a length of 104 in., and produces a very uniform flow, with turbulence level less than 0.1% over a wind speed range 0-150 fps. The airfoil models were mounted vertically on the yaw turntable of the 6-component wind tunnel balance, and spanned the 27 in. height of the test section at the tunnel center-line, except for very small clearances from the tunnel floor and ceiling. The gap through which the spar attaching the models to the balance turntable pierced the floor was kept closed to very small clearances, and the floor and ceiling were otherwise solid. The tunnel test section has 6 in. by 6 in. corner fillets (actually tapered downstream to compensate for boundary layer growth), so that the section area is 900 sq.in., and the effective tunnel width H, for use in wall correction theory, is the area divided by the height (as recommended in Reference (1)), or 33.3 in.

Because of the presence of the corner fillets, which contain fluorescent lights, the side wall panels which can be given different configurations of longitudinal slots are only 15 in. high by 104 in. Two frames for panels of this size were constructed to be filled with longitudinal wooden strips 1 in. thick and of various widths, so that the side walls could be completely solid or have a distribution of longitudinal slots 1 in. deep and of various widths. The slot configurations for which results are presented here are designated by their open area ratio r, the ratio of the total slot width in one side panel to the 27 in. test section height. The configurations were as follows. For $r = \frac{1}{18} = .056$, the 15 in. panel width consisted of three $\frac{1}{2}$ in. wide slots, one at each edge and one in the center, with two solid sections each $6\frac{3}{4}$ in. wide between. For $r = \frac{1}{9} = .111$, the three slots were each 1 in. wide. For $r = \frac{5}{27} = .185$, the three slots were each 1 2/3 in. wide. For $r = \frac{8}{27} = .296$, the 15 in. panel width consisted of eight 1 in. wide slots alternating with seven 1 in. wide solid strips.

Two sets of four airfoils each were constructed, mainly of wood. Chord sizes C in each set were 9 in., 14 in., 19 in. and 24 in. In one set the profile was a Clark Y airfoil of 14% thickness. In the other set the same profile was given a fixed slot at mid-chord and a slotted flap set at 45°, identical with one of the profiles tested by Weick and Shortal[2], except for the modification of the thickness from 11.7% to 14%. These profiles were selected because of their simplicity and established good performance at the moderate Reynolds numbers available in the tunnel used.

Preliminary tests established that Reynolds number effects were small in the N_R-range used, but in fact all subsequent tests were carried out at nearly constant N_R, approximately $3(10)^5$. It was also established that in the presence of both solid and slotted walls the loading on the airfoils was closely two-dimensional below the stall.

For each combination of an airfoil and a wall configuration tested, lift, drag and pitching moment about mid-chord were measured through a full range of angle of attack α from below zero lift to beyond the stall, with increasing and decreasing readings. Data were quite consistent and repeatable, and averaged values were calculated and presented as lift, drag and quarter-chord moment coefficients C_L, C_D, $C_{M_{c/4}}$, conventionally defined.

III. Experimental Results

Figs. 1 - 7 give samples of the variation of C_L and $C_{M_{c/4}}$ with α for the four values of c/H for both profiles in the presence of solid and slotted walls. No C_D values are presented because, although they were consistent and of the right magnitude for the profiles at the test N_R, they were quite small ($C_{D_{MIN}} = .016$ for the basic Clark Y profile) and they could not be measured precisely enough to permit useful conclusions to be drawn about the effects of model size and wall configuration.

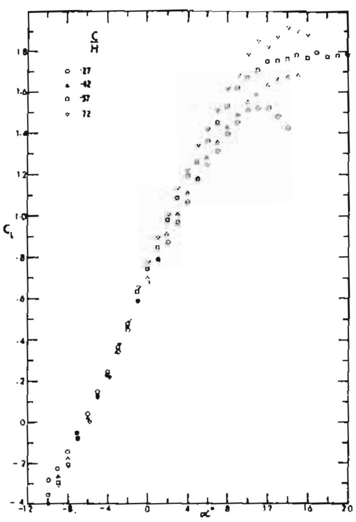

Figure 1. Basic profile. Solid walls. r = 0

Fig. 1 shows that zero lift angle α_z for the basic profile in the presence of solid walls is about - 6.5°, independent of c/H, but that lift curve slope $m = \frac{dC_L}{d\alpha}$ increases with c/H. $C_{L_{MAX}}$ is also seen to increase with c/H.

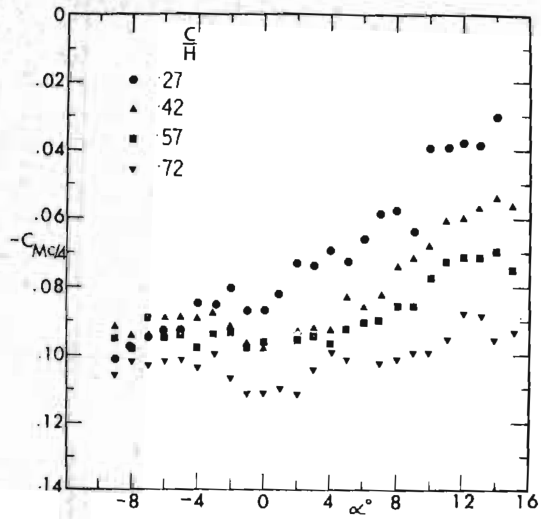

Figure 2. Basic profile. Solid walls.
$r = 0$

In Fig. 2 for the same configurations as Fig. 1, the magnified scale emphasises the scatter in the data, but the trend to increased negative $C_{M_{c/4}}$ with increasing c/H is clear.

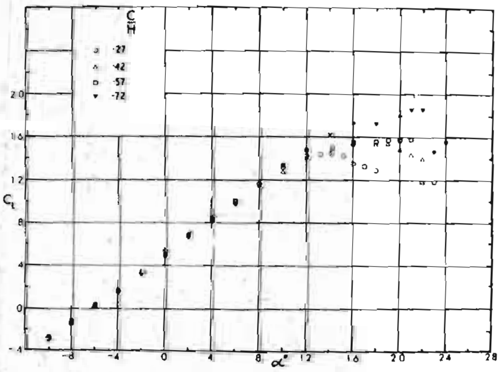

Figure 3. Basic profile. Slotted walls.
$r = .111$

Fig. 3 for the basic profile in the presence of slotted walls again shows $\alpha_z = -6.5°$ independent of c/H, and in addition shows m almost independent of c/H below the stall, which might suggest this open area ratio ($r = .111$) as a configuration giving lift data with negligible wall corrections. However, the mean value of m is found to be .083 per degree, whereas the correct sectional value m_o is known to be considerably higher at the test N_R (.098 per degree is used in subsequent theoretical calculations).

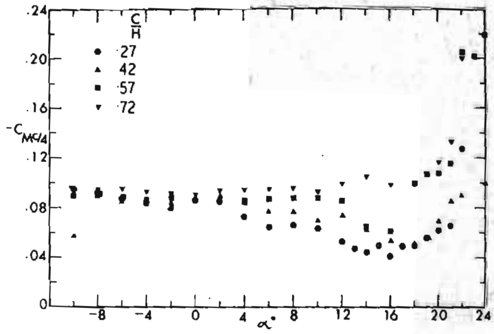

Figure 4. Basic profile. Slotted walls.
$r = .111$

In Fig. 4, for the same configurations as Fig. 3, the same trends as in Fig. 2 can be seen, but much reduced in magnitude below $\alpha = 4°$.

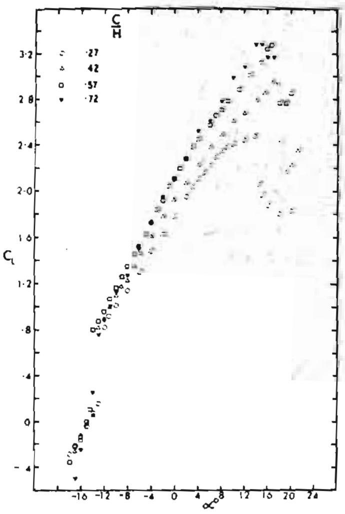

Figure 5. Profile with slot and slotted flap. Solid walls. $r = 0$

Fig. 5, for the profile with slot and slotted flap, like Fig. 1 shows m increasing with c/H below the stall, and shows $C_{L_{MAX}}$ increasing with c/H. Here, however, C_L values are all much higher, and the negative stall is reached with C_L still positive. Again α_z is nearly independent of c/H at $-15°$.

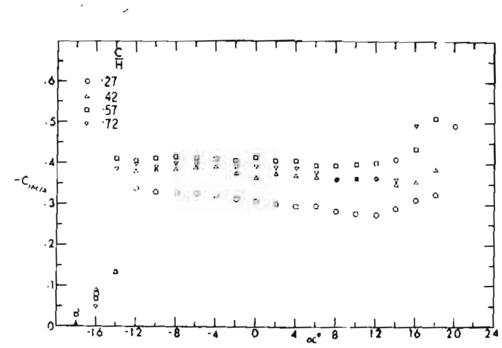

Figure 6. Profile with slot and slotted flap. Solid walls. r = 0

Fig. 6, for the same configuration as Fig. 5, shows consistent data for each airfoil of the set, but the relatively small negative values of $C_{M_{c/4}}$ for the 9 in. airfoil, and the more negative values for the 19 in. than for the 24 in. airfoil suggest that small geometric differences in the four airfoils have contributed effects of the same order as the effects of c/H. Accordingly, no attempt is made to correlate $C_{M_{c/4}}$ data from airfoils of this profile with theory.

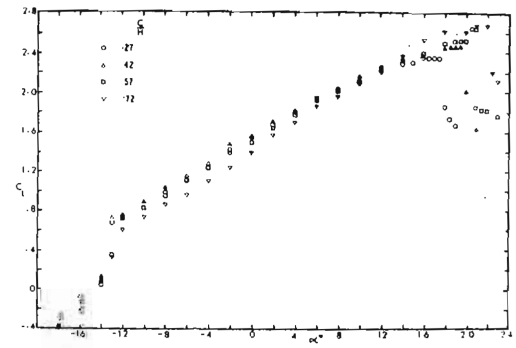

Figure 7. Profile with slot and slotted flap. Slotted walls. r = .185

Fig. 7, for the flapped profile in the presence of slotted walls, shows that α_z = − 15°, independent of c/H, as in Fig. 5, but the data for the four airfoils between negative and positive stall have approached collapse to a single curve.

The experimental results will now be examined in the light of available wall correction theory.

IV. Theory

The theory of wind tunnel wall corrections is based on the assumption that the flow inside the test section, as disturbed by the presence of the model, is inviscid and irrotational, so that a disturbance velocity potential ϕ exists. For low speed flow, the air can be considered incompressible, and ϕ obeys Laplace's differential equation, which is linear. For solid tunnel walls, the boundary condition is that the normal component of disturbance velocity vanishes:

$$\frac{\partial \phi}{\partial n} = 0 \tag{1}$$

while for an open jet, it is assumed that the disturbance from the model at the jet boundary is small and causes negligible displacement of the boundary, from which the linearized condition of constant pressure at the jet boundary can be expressed, using Bernoulli's equation, by the vanishing of the streamwise disturbance velocity there,

$$\frac{\partial \phi}{\partial x} = 0 \quad . \tag{2}$$

For slotted or perforated walls, a linear combination of these boundary conditions is used. The following discussion is based mainly on Ch. 6 of Ref. 1, by Rogers.

Longitudinal slots

For walls with longitudinal slots an equivalent homogeneous boundary condition is used, based on a potential flow model of the cross flow through the slots,

$$\frac{\partial \phi}{\partial x} + K \frac{\partial^2 \phi}{\partial x \partial n} = 0 \tag{3}$$

where $$K = \frac{d}{\pi} \ln \csc \frac{\pi r}{2} \tag{4}$$

and d is the slot spacing, with r and d assumed small. Using suitable singularities to represent the effects of the model and its wake, Laplace's equation is solved so as to satisfy Eq. (3), and the following wall corrections are determined.

Solid and wake blockage factors ϵ_s and ϵ_w are the fractional increments to the reference tunnel speed, upon which corrected model force and moment coefficients are based, caused by the constricted flow past the model. It is convenient to present them as fractions Ω_s and Ω_w of the corresponding factors ϵ_{s_c} and ϵ_{w_c} for closed walls, where, by conventional theory for solid walls(3),

$$\epsilon_{s_c} = \Lambda \frac{\pi^2}{48}\left(\frac{c}{H}\right)^2 \quad (5)$$

$$\epsilon_{w_c} = \frac{C_D}{4}\left(\frac{c}{H}\right) \quad (6)$$

Equations for calculating Ω_s and Ω_w are given in Ch. 6 of Ref. 1, and Ω_s is plotted as a function of $\frac{1}{\sqrt{1+2K/H}}$ in Fig. 6.4 there. Thus the corrected tunnel reference speed U_o is given by

$$U_o = U\left(1 + \Omega_s \epsilon_{s_c} + \Omega_w \epsilon_{w_c}\right) \quad (7)$$

where U is the measured reference speed. The theory for longitudinal slots is applied below only to the basic profile, for which C_D is very small, so that the term $\Omega_w \epsilon_{w_c}$ is omitted.

The remaining wall corrections to be determined are the upwash and streamline curvature interference factors δ_o and δ_1, which arise from the airfoil lift characteristics. They appear in the formula for the correction to angle of attack, $\Delta\alpha$:

$$\Delta\alpha = \delta_o C_L\left(\frac{c}{H}\right) + \delta_1\left(\frac{C_L}{4} + C_{M_{c/4}}\right)\left(\frac{c}{H}\right)^2 \quad (8)$$

and residual corrections due to streamline curvature are conveniently expressed as equivalent increments to C_L and $C_{M_{c/4}}$, in terms of δ_1 :

$$\Delta C_L = -\frac{\pi}{2}\delta_1 C_L\left(\frac{c}{H}\right)^2 \quad (9)$$

$$\Delta C_M = \frac{\pi}{8}\delta_1 C_L\left(\frac{c}{H}\right)^2 \quad (10)$$

Equations for calculating δ_o and δ_1 are given in Ch. 6 of Ref. 1 and values of each are plotted as functions of $\frac{1}{1+2K/H}$ in Fig. 6.15 there.

Perforated walls

For walls with a pattern of holes through which a cross-flow takes place, the linearized boundary condition is based on the assumption that the pressure difference δp across the wall is proportional to the effective normal disturbance velocity at the wall,

$$\delta p = \rho U/P \, \partial\phi/\partial n$$

where ρ is air density and P is the porosity parameter, or resistance coefficient, assumed constant for a given wall geometry. This gives the boundary condition

$$\frac{\partial\phi}{\partial x} + \frac{1}{P}\frac{\partial\phi}{\partial n} = 0 \quad (11)$$

Rogers suggests that P must be determined experimentally for a particular wall g geometry, but mentions theoretical values proposed for two-dimensional wall conditions (where the porosity consists of transverse slots), such as that of Woods[4], in which, for closely perforated walls,

$$P = \tan\frac{\pi}{2} r \ . \quad (12)$$

The same wall correction factors Ω_s, Ω_w, δ_o and δ_1 are calculated for the new boundary conditions, and are used in the same way, so that Eqs. (5) - (10) apply also for perforated walls. Woods, in Ref. 4, works out the correction factors for a finite length R of the tunnel test section, as follows:

$$\Omega_s = 1 + 6k^2\sigma^2 - 6k\sigma \tanh\frac{\pi kR}{2H} \quad (13)$$

$$\Omega_w = 1 + 2k\sigma - 2\tanh\frac{\pi kR}{2H} \quad (14)$$

$$\delta_o = -\frac{k\sigma}{2} \quad (15)$$

$$\delta_1 = \frac{\pi}{24}\left(1 - 12k^2\sigma^2\right) \quad (16)$$

where $k = \frac{1}{\pi}\arctan P$, $\sigma = \tanh\frac{\pi R}{2H}$

Rogers, on the other hand, in Ch. 6 of Ref. 1, presents values only for infinite R. This makes little difference to δ_o and δ_1 for most tunnel test sections, since $\sigma > .98$ for $R > 1.5H$, but it makes a considerable difference to Ω_s and Ω_w, because of the last term in Eqs. (13) and (14). In fact, if R is made infinite in Eq. (14), for arbitrary k, the equation becomes

$$\Omega_w = 2k - 1 \quad (17)$$

so that Ω_w becomes - 1 instead of + 1 in the limiting case of solid walls (k = 0). These differences are shown in Fig. 8, where Ω_s and Ω_w are plotted against 1/P for $\frac{R}{H} = 2$ and ∞ . In the following section, predictions from the above theories are compared with the experimental results of III.

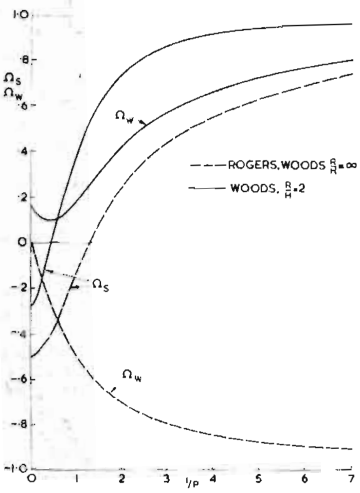

Figure 8. Theoretical solid and wake blockage factors for porous walls

V. Comparisons

Lift correction theory could be compared with the above experiments by applying the corrections of Eqs. (7), (8) and (9) to the data points, and examining the tendency to collapse to the expected curve for free air conditions. Instead, another approach was chosen for its simplicity and ability to show trends. Figs. 1 and 3, and to a lesser extent Figs. 5 and 7, indicate that the variation of C_L with α for a given profile below the positive stall is characterised satisfactorily by 2 parameters, α_z and an average value of m, and only m varies appreciably with c/H or with the wall configuration. (In applying this argument to the airfoil with slot and slotted flap, as in Figs. 5 and 7, it is convenient to imagine a fictitious α_z, determined by the continuation of the C_L-α curves from above the negative stall down to zero lift). Accordingly, the lift correction theories are compared with experiment in the form of m/m_o as a function of c/H for each profile and wall configuration.

Using $(\;)_o$ to denote free air values ($c/H = 0$):

$$m = \frac{C_L}{\alpha - \alpha_z}\,, \quad m_o = \frac{C_{L_o}}{\alpha_o - \alpha_{z_c}} = \frac{C_L + \Delta C_L}{\alpha + \Delta\alpha - \alpha_z - \Delta\alpha_z}\left(\frac{U}{U_o}\right)^2$$

so that, using Eqs. (7), (8), (9), (10):

$$\frac{m}{m_o} = \frac{1 + m_o\{\delta_o(\frac{c}{H}) + \frac{\delta_1}{4}(\frac{c}{H})^2\}\frac{m}{m_o}}{1 - \frac{\pi}{2}\delta_1(\frac{c}{H})^2}\left(1 + \Omega_s\epsilon_{s_c} + \Omega_w\epsilon_{w_c}\right)^2$$

Solving for $\frac{m}{m_o}$, and retaining terms of order $(\frac{c}{H})^2$, to be consistent with the derivation of Eqs. (5) - (10):

$$\frac{m}{m_o} = 1 + \left(m_o\delta_o + \Omega_w\frac{C_D}{2}\right)\left(\frac{c}{H}\right) + \left\{m_o^2\delta_o^2 + \left(\frac{\pi}{2} + \frac{m_o}{4}\right)\delta_1 + \Omega_s\Lambda\frac{\pi^2}{24} + \Omega_w C_D m_o\delta_o + \Omega_w^2\frac{C_D^2}{16}\right\}\left(\frac{c}{H}\right)^2 \quad (18)$$

Pitching moment correction theory is applied directly in the form of Eq. (10), but the experimental data is adjusted to account for the aerodynamic center not being exactly at the quarter-chord point, so that the theoretical and experimental values of $\frac{\Delta C_M}{C_L}$ are made to agree for the smallest airfoil ($\frac{c}{H}$ = .27) in each case.

Eqs. (10) and (18) can be applied for solid walls by taking

$$\Omega_s = \Omega_w = 1, \quad \delta_o = 0, \quad \delta_1 = \frac{\pi}{24}\,.$$

For the basic profile, m_o = .098 per degree = 5.6 per radian, and terms involving C_D are neglected. For the flapped profile, m_o = .074 per degree = 4.2 per radian, and averaged values of C_D are used, .22 in the presence of solid walls and .25 in the presence of slotted walls. The solid blockage shape factor Λ = .28 for both the basic and flapped profile.

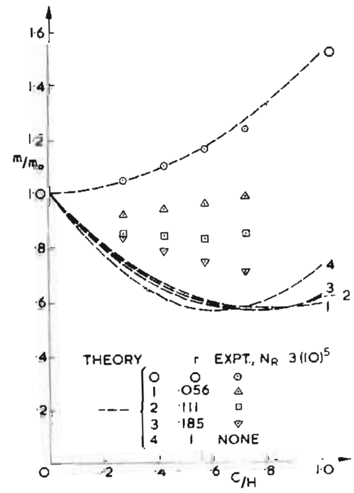

Figure 9. Comparison of slotted-wall lift theory with data for basic profile

In Fig. 9, the theory for longitudinal slots of IV has been used to determine Ω_s, δ_o and δ_1 to substitute in Eq. (18) for the basic Clark Y profile in the presence of slotted walls with three different open-area ratios, as well as for solid walls and an open jet. It is seen that, whereas the theory for solid walls gives excellent agreement with the data, the theory for slotted walls is useless, with the curves for all values of r closely grouped, as though all of the wall configurations were effectively open. As a result, no further calculations of this theory were made. Instead, the theory of perforated walls was applied to the configurations tested, with values of P determined empirically so that the theory gave as good agreement as possible with the lift data.

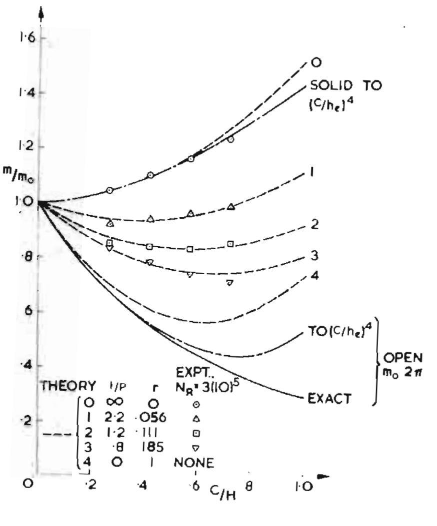

Figure 10. Comparison of porous-wall lift theory with data for basic profile

In Fig. 10 the perforated-wall theory is applied to the same configurations as in Fig. 9, and here it is seen that values of P were found that produced good agreement with data for the three values of r tested. The curves for solid walls and open jet from Fig. 9 are repeated, and the effect of higher order terms in C/H, known for these cases and given in Refs. 1 and 4, is also shown. The effect is seen to be significant, particularly for the open jet.

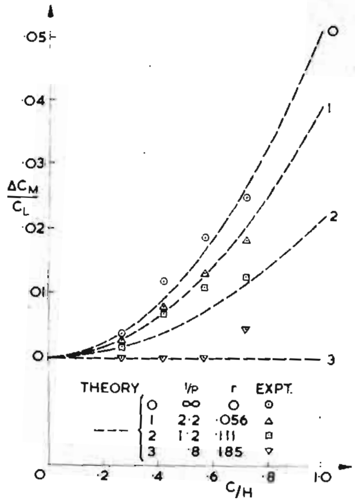

Figure 11. Comparison of porous-wall moment theory with data for basic profile

In Fig. 11, the theoretical pitching moment corrections for the configurations of Fig. 10 are calculated for the same values of P used for the lift comparisons, and are seen to produce quite good agreement with the data for solid walls and two of the slotted-wall configurations. Agreement with the third slotted-wall case, with r = .111, is only fair.

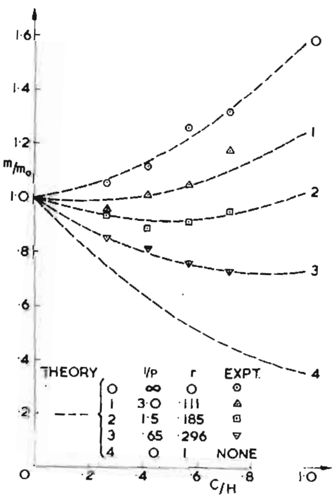

Figure 12. Comparison of porous-wall lift theory with data for flapped profile

In Fig. 12, the perforated-wall theory is applied to the profile with slot and slotted flap in the presence of longitudinally slotted walls of three different open-area ratios. Curves for solid walls and open jet are also presented. It is seen that the solid-wall theory gives excellent agreement with the data, as before, and that again values of P were found which produced good agreement with the data for the three values of r. However, for the same values of r as in Fig. 10, the appropriate values of P were lower for the flapped profile than for the basic profile

VI. Discussion

Fig. 9 shows that the theory of ideal longitudinally slotted walls is useless for calculating the wall corrections for low-speed two-dimensional airfoil tests in the presence of actual longitudinally slotted walls. Figs. 10, 11 and 12, on the other hand, indicate a possibility of using the theory developed for perforated walls for the same purpose. However, this theory requires knowledge of the porosity parameter P. If P could be calculated from a specification of the wall geometry, then the theory would be quite attractive, since Figs. 10 and 11 show that a value of r could be selected which would make the wall corrections for either lift or moment small. Even if P could be determined experimentally as a constant for a given wall geometry, independent of the model to be tested, that might be satisfactory. However, Fig. 13 shows that the situation is more complex.

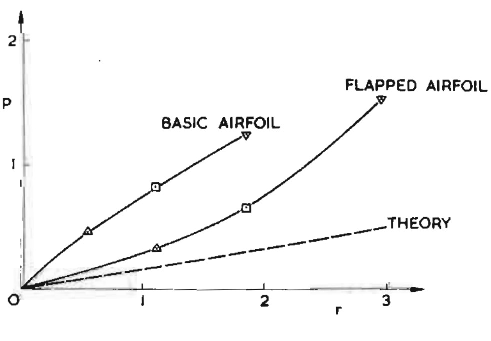

Figure 13. Porosity parameter as a function of open-area ratio

It is seen that there are two completely different variations of P with r for the two profiles tested, and neither of them agrees with the theoretical variation of Eq. (12), although each gives the same qualitative trend as the theory. Thus, P depends not only upon the wall geometry, but on the model under test, an impossible situation for practical use of the theory.

Possibly the dependence of P on the model under test is related to the need for a non-linear boundary condition to replace Eq. (11). If δp across the wall were actually proportional to $\left(\frac{\partial \phi}{\partial n}\right)^2$, then $1/P$ would be proportional to $\frac{\partial \phi}{\partial n}$, and this might explain the higher values of $1/P$ needed to produce agreement for the flapped airfoil, which would create higher values of $\frac{\partial \phi}{\partial n}$ at the wall. Wood[5] has applied such a non-linear boundary condition in the theory for wall corrections to a non-lifting two-dimensional airfoil, but further applications of this technique do not seem to have been made.

Figs. 10, 11 and 12 show that the conventional theory of wall corrections to order $\left(\frac{c}{H}\right)^2$ for solid walls gives very good agreement with lift and pitching moment data in low-speed two-dimensional airfoil tests, even for (c/H) as large as .72, and that further improvement can probably be obtained by calculating higher order terms. Therefore, in the absence of improvements to the theory for slotted-or perforated-wall corrections, it seems advisable to carry out low-speed two-dimensional airfoil tests even for large models, developing high lift coefficients, in conventional wind tunnels with solid walls.

VIII. Acknowledgements

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