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DESIGN AND CALIBRATION OF SLOTTED WALLS FOR TRANSONIC AIRFOIL WIND TUNNELS

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SUMMARY

The traditional procedure for estimating the performance of slotted walls for airfoil wind tunnels is reviewed, and a modification which improves the accuracy of this procedure is described. Unlike the traditional procedure, the modified procedure indicates that the design of airfoil wind-tunnel walls which induce minimal blockage and streamline-curvature effects is feasible. The design and testing of such a slotted wall is described. It is shown experimentally that the presence of a model can affect the plenum pressure and thus make the use of the plenum pressure as a calibration reference questionable. Finally, an ONERA experiment which shows the effect of the sidewall boundary layer on the measured model normal force is discussed.

INTRODUCTION

Slotted walls have been used to reduce blockage in transonic wind tunnels for three decades. Traditionally, the performance of these walls has been estimated with a theoretical procedure based on the results of Davis and Moore (ref. 1); Baldwin, Turner, and Knecthel (ref. 2); and Wright (ref. 3). It is generally known that this traditional procedure does not work.

The analysis of the effects of slotted walls involves three general steps. First, a model of the flow in the vicinity of the wall must be developed. It will be shown that this flow model is a function of one parameter which depends on the wall geometry. Next, the interference for various values of the flow-model parameter must be determined. Finally, the flow-model parameter must be evaluated for a given wall geometry. In the past, it has been assumed generally that the last step was performed correctly with the theoretical method of Davis and Moore (ref. 1), and that the failure of the traditional procedure was due to one or both of the other steps. Recent work by Barnwell (ref. 4) indicates instead that the failure of the traditional procedure is due largely to the manner in which the third step has been performed. An alternate method for performing the third step, which is based on experimental data rather than theory, is presented in this paper.

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It is standard practice to use the plenum pressure as a reference for the calibration of transonic wind tunnels. The validity of this approach has been demonstrated for three-dimensional testing where the maximum model cross-sectional area is constrained to be a fraction of 1 percent of the tunnel cross-sectional area. However, this constraint is not met, in general, in two-dimensional tunnels where, instead, maximum model cross-sectional areas are typically from 2 to 4 percent of the tunnel cross-sectional area. It should not be too surprising that the presence of such a model would influence the plenum pressure and thereby make its use as a reference pressure unreliable. Experimental results for a sample case in which this phenomenon occurred are presented.

Results obtained in the ONERA R1Ch wind tunnel (ref. 5) which show that the sidewall boundary layer can have a substantial effect on the normal force measured on the model are discussed. A possible explanation for this effect is presented.

SYMBOLS

a	slot spacing
c_n	normal-force coefficient
h	tunnel semiheight
K	slotted-wall coefficient
k	flow-model parameter
M	Mach number
M_∞	free-stream Mach number
M_{PLENUM}	Mach number based on plenum pressure
x	coordinate in free-stream direction
y	coordinate perpendicular to free-stream direction
α	angle of attack
β	$= \sqrt{1 - M_\infty^2}$
δ	slot width
δ^*	displacement thickness
θ	flow angle with respect to free-stream direction

Subscript:

max maximum value

ANALYSIS OF SLOTTED WALLS

Flow Model at Wall

The first step of the analysis procedure is to develop a model of the flow near a slotted wall. The simplest form of this model, which was developed independently by Davis and Moore (ref. 1) and Baldwin, Turner, and Knecthel (ref. 2), among others, is the form used in this paper. A more complete form is given in references 4 and 6.

The flow in a slotted-wall tunnel is depicted in figure 1. The tunnel has a height of 2h. The coordinates in the free-stream and vertical directions are x and y, respectively. The angle which a streamline makes with respect to the free-stream direction is θ. Longitudinally slotted walls are located between the tunnel and the plenum. A cross section of these walls is shown on the right-hand side of figure 1. The slot width is δ and the slot spacing is a.

The flow model for slotted walls is obtained from the ideal slot condition, which states that the static pressure at the slot is equal to the plenum pressure. The boundary condition which results is

$$C_{p,w} = 2k \frac{\partial \theta_w}{\partial x/h} \tag{1}$$

where $C_{p,w}$ and θ_w are the pressure coefficient and flow angle in the tunnel near the wall, and k is the flow-model parameter. This parameter is a function of tunnel geometry.

Interference Effects

The next step of the analysis procedure is to determine the interference effects for various values of the flow-model parameter k. Baldwin, Turner, and Knecthel (ref. 2) and Wright (ref. 3) determined these effects for two-dimensional flow theoretically using the boundary condition given in equation (1). A comprehensive treatment of wall interference effects is given by Pindzola and Lo (ref. 7).

The downwash and blockage interference along the center line of two-dimensional slotted-wall wind tunnels is presented in figure 2. It should be noted that the downwash interference is the effect of the wall on the velocity component perpendicular to the free-stream direction, and the blockage interference is the effect of the wall on the velocity component in the free-stream direction. The distance x has been made nondimensional with the quantity βh. The model depicted in figure 2 is scaled for a tunnel-height—model-chord ratio of 4, which is a typical value for two-dimensional transonic testing, and a free-stream Mach number of 0.85.

Consider the downwash effect first. It can be seen that this effect decreases from front to rear on a model in a closed tunnel ($k = \infty$) and increases from front to rear on a model in an open tunnel ($k = 0$). In both cases, the variation of downwash along the model is substantial for the case depicted in the figure. It can also be seen that, if the flow-model parameter k has a value of about 1.5, the downwash effect is almost constant along the model and for some distance ahead of and behind it. If this value of the flow-model parameter could be obtained, the streamline-curvature effect would be negligible, and a constant-downwash correction would suffice.

Now consider the blockage effect. Note that this effect is symmetric about the model location for slotted walls. (This is not the case for porous walls.) It can be seen that the blockage effect near the model is positive for a closed tunnel ($k = \infty$) and negative for an open tunnel ($k = 0$). This observation indicates that this effect causes the flow to speed up as it passes a model in a closed tunnel and slow down as it passes a model in an open tunnel. It can also be seen that, if the flow-model parameter k has a value of about 1.2, the blockage effect at the origin is zero. In addition, it can be observed that the average blockage effect along the model will be zero if the value of k is slightly larger than 1.2. It is concluded that both streamline-curvature and blockage effects can be minimized effectively if the flow-model parameter has a value of about 1.5.

Flow-Model Parameter

The last step of the analysis procedure is to evaluate the flow-model parameter k for a particular wall geometry. This parameter is usually written in the form

$$k = \frac{c}{h} K \qquad (2)$$

where K is the slotted-wall coefficient. A theoretical solution for the coefficient K was obtained independently by Davis and Moore (ref. 1); Baldwin, Turner, and Knecthel (ref. 2); and others. This solution, which is depicted in figure 3, is for flat walls with sharp-edged slots. A different theoretical solution was developed by Chen and Mears (ref. 8). Barnwell (ref. 9) corrected an error in the solution of Chen and Mears and showed that the corrected solution, which is shown in figure 3, differs from that of Davis and Moore because the wall associated with the corrected solution of Chen and Mears is curved and has rounded slot edges. It should be noted that both of the solutions depicted in figure 3 are functions of the tunnel-wall openness ratio δ/a and are independent of the slot-spacing—tunnel-semiheight ratio a/h.

Only three experimentally determined values for the slotted-wall coefficient K (refs. 8, 10, and 11) are known to have been published prior to this conference. These values are depicted with solid symbols in figure 3. A fourth experimental value can be inferred from the unpublished results of J. Osborne[1]. All four of these experiments were performed with symmetrical, nonlifting models. However, the Mach numbers and Reynolds numbers differ considerably.

It can be observed from figure 3 that the experimental data are self-consistent, and that neither of the theories agrees with the data. In fact, the values obtained from the most widely used theory, that of Davis and Moore, are consistently about one-fourth as large as the corresponding experimental values. In this paper, values for the slotted-wall coefficient K are obtained from the experimental data rather than from theory.

It should be noted that Everhart and Barnwell (ref. 6) have conducted a parametric study which has substantially increased the experimental data for the coefficient K. These data have the same type of dependence on the openness ratio δ/a shown in figure 3. However, the new data also indicate a dependence on the slot-spacing—tunnel-semiheight ratio a/h.

LOW-INTERFERENCE DESIGN

The procedure described in the previous section has been used to design a low-interference wall for the Langley 6- by 28-inch transonic wind tunnel. The data for the coefficient K shown in figure 3 rather than those presented in reference 6 were used in the design because the experiment described in reference 6 had not been performed then.

In the discussion of figure 2, it was concluded that the flow-model parameter k for a minimum-interference tunnel has a value of about 1.5. The designer must choose the number of slots the wall will have. Once this choice is made, the value of the slotted-wall coefficient K can be obtained from equation (2), and the value of the wall openness ratio δ/a can be obtained then from figure 3. Results for one, two, and four slots are given in the table below. On the basis of these results, the design involving one

Number of slots	K	Openness ratio
1	3.5	0.05
2	7	0.02
4	14	Very small

[1]Aerodynamics Department, Royal Aircraft Establishment.

slot was chosen. This choice was based on a desire to keep the crossflow in the slot from becoming sonic and choking as a result. Since the crossflow in the slot varies inversely with the openness ratio (see ref. 4), it is desirable to keep the openness ratio relatively large.

It should be noted that a minimum-interference tunnel would not be feasible if the theory of Davis and Moore were correct because that theory indicates that the slot openness ratio would have to be much less than 0.01 even for a one-slot configuration. This small an openness ratio would definitely exhibit the choked-crossflow behavior discussed above.

In figure 4, the results of theory and experiment for the wall-induced downwash in the Langley 6- by 28-inch transonic tunnel are compared. The results for the new wall and the previous wall (ref. 12) are depicted with a square and a circle, respectively. The experimental values were determined from comparisons of lift curves obtained in the 6- by 28-inch transonic tunnel and the Langley low-turbulence pressure tunnel. The latter tunnel is closed and hence should have no lift interference due to the top and bottom walls except that caused by streamline curvature. The closed-tunnel data were corrected for streamline-curvature effects with the method of Allen and Vincenti (ref. 13).

WIND-TUNNEL CALIBRATION

In general, either the plenum pressure or an upstream pressure is used as a reference for the calibration of transonic wind tunnels. Results are presented in figure 5 which show that the presence of a model can influence the plenum pressure and thus make its use as a reference pressure unreliable. The data presented in the figure were obtained by Everhart and Barnwell during the course of the experiment described in reference 6. The data shown are the Mach number based on plenum pressure M_{PLENUM} and the Mach number distribution along an orifice row on the tunnel sidewall near the top wall. This orifice row is one of those depicted schematically in figure 2 of reference 6.

Results are presented for two Mach numbers based on plenum pressure both with and without the model in the tunnel. It can be seen that for $M_{PLENUM} \approx 0.9$, the presence of the model causes M_{PLENUM} to increase relative to the upstream Mach number in the tunnel by approximately 0.03. For $M_{PLENUM} \approx 0.7$, the incremental increase in M_{PLENUM} due to model presence is reduced to about 0.01. Apparently, the plenum pressure is influenced by the flow through the slot, and this flow is influenced by the presence of the model. At transonic speeds the influence of the model is stronger at the wall and the effect on the plenum pressure is greater. It is concluded that, for this tunnel configuration at least, the pressure at an upstream orifice should be used as a calibration reference pressure.

SIDEWALL BOUNDARY-LAYER EFFECT

There are very few experiments which show quantitatively the effect of the sidewall boundary layer on the flow in the tunnel. One such experiment has been performed in the ONERA R1Ch wind tunnel (ref. 5), which is shown schematically in figure 6. Although this tunnel has porous top and bottom walls and a transonic capability, the experiment described here was performed with $M_\infty \approx 0.3$ and solid top and bottom walls. The tunnel is equipped with porous sidewalls and sidewall plena to which suction can be applied.

The experiment consisted of the measurement of the normal force on a model at a fixed angle of attack for different sidewall boundary-layer thicknesses. First, the sidewall boundary layer was measured near the model station in an empty tunnel for various values of the sidewall suction rate. Then the model was inserted and the chordwise pressure distribution was measured for the same values of the suction rate. The normal-force coefficients obtained from these pressure distributions are plotted in terms of the nondimensional tunnel-empty displacement thickness on the right-hand side of the figure. As pointed out in reference 5, the dependence of the normal-force coefficient on the displacement thickness is linear. It can be seen that, for this experiment, the apparent normal-force coefficient for zero sidewall displacement is about 10 percent greater than the normal-force coefficient for no suction.

This lift reduction may be due to the manner in which lift influences the growth of the boundary layer on the sidewall of the tunnel near the model. The effect of lift is to increase the flow speed above the model and reduce it beneath. Above the model the increased flow speed causes the sidewall boundary layer to thin somewhat so that the effective cross-sectional area above the wing is increased slightly. Consequently, the airspeed above the model is somewhat less than that for true two-dimensional flow so that the pressure on the suction side is slightly too high. Beneath the model, the opposite effects occur so that the pressure on the compression side is a little too low. The effect of reducing both the suction above the model and the compression beneath the model is to reduce the lift.

CONCLUDING REMARKS

A procedure for designing slotted walls for transonic wind tunnels has been developed. The measured downwash in a two-dimensional tunnel equipped with slotted walls designed with this procedure is in good agreement with the predicted value. Experimental results are presented which show that the plenum pressure is influenced by the presence of a model in the tunnel. It is concluded that the plenum pressure is not always a reliable calibration reference pressure. An ONERA experiment which shows the effect of the sidewall boundary layer on the measured model normal force is discussed, and a possible explanation for the observed effect is presented.

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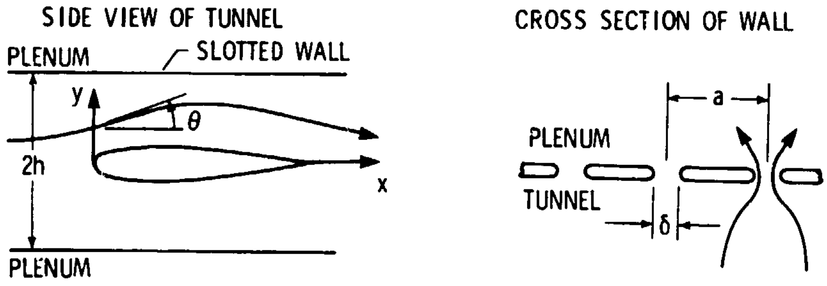

Figure 1.- Flow in slotted-wall tunnel.

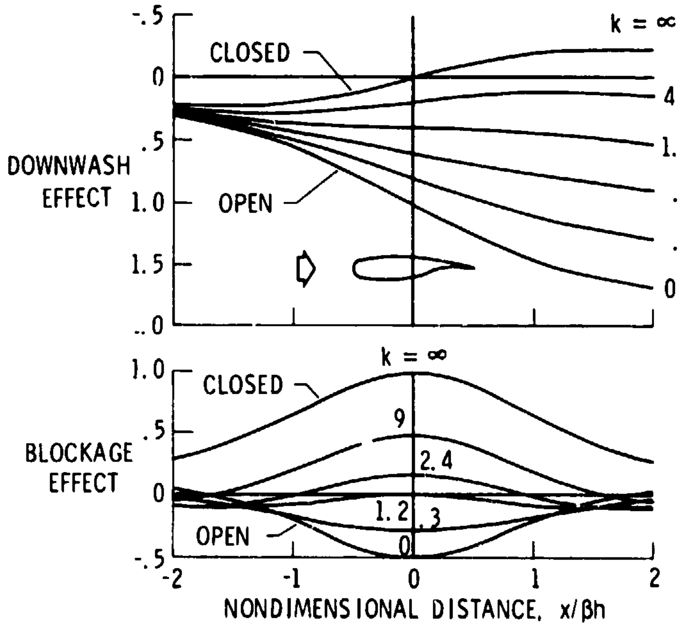

Figure 2.- Two-dimensional slotted-wall interference along tunnel center line.

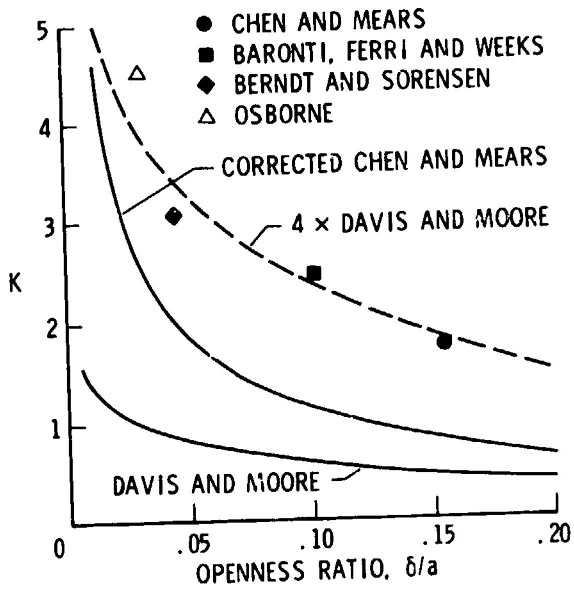

Figure 3.- Slotted-wall coefficient.

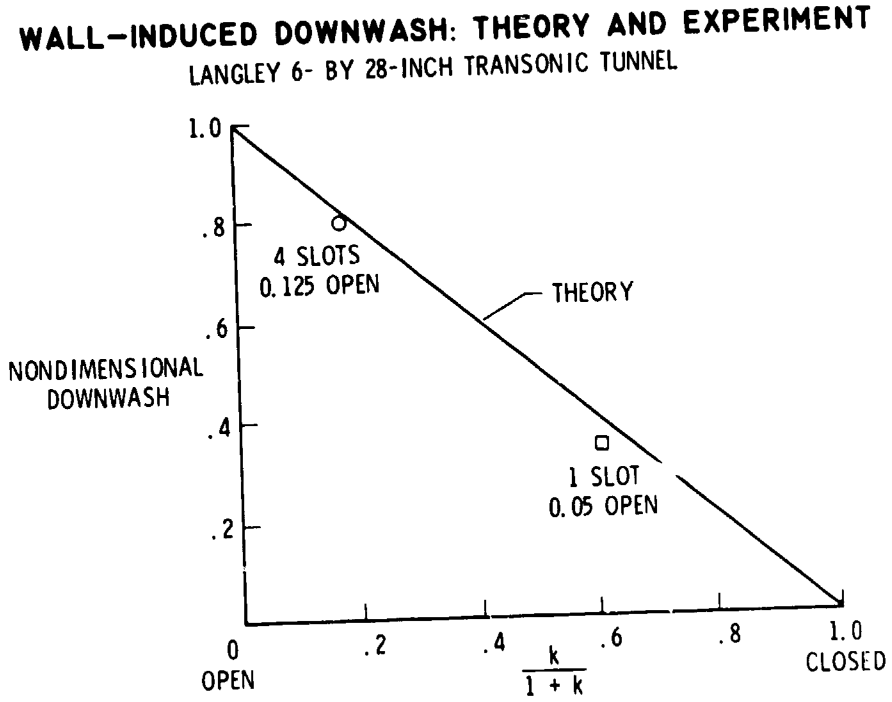

Figure 4.- Comparison of theory and experiment for wall-induced downwash in the Langley 6- by 28-inch transonic tunnel.

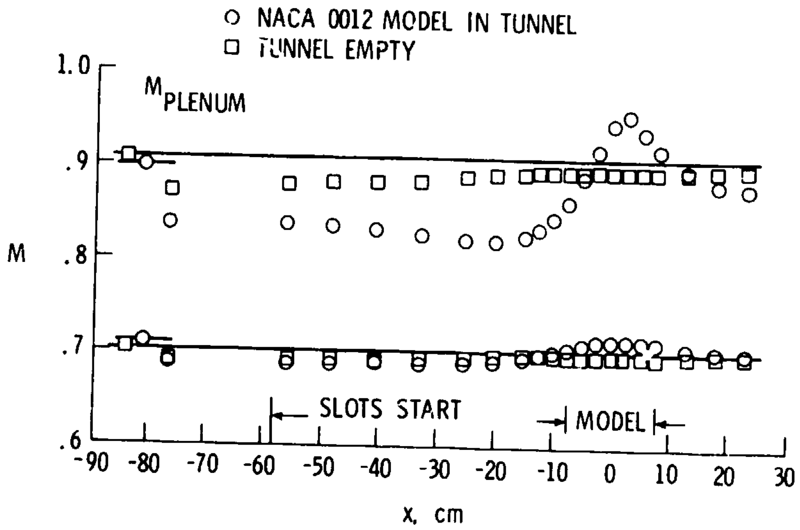

Figure 5.- Mach-number distribution on sidewall and Mach number based on plenum pressure for experimental configuration of Langley 6- by 19-inch transonic tunnel. Two slots; wall openness ratio, 0.05.

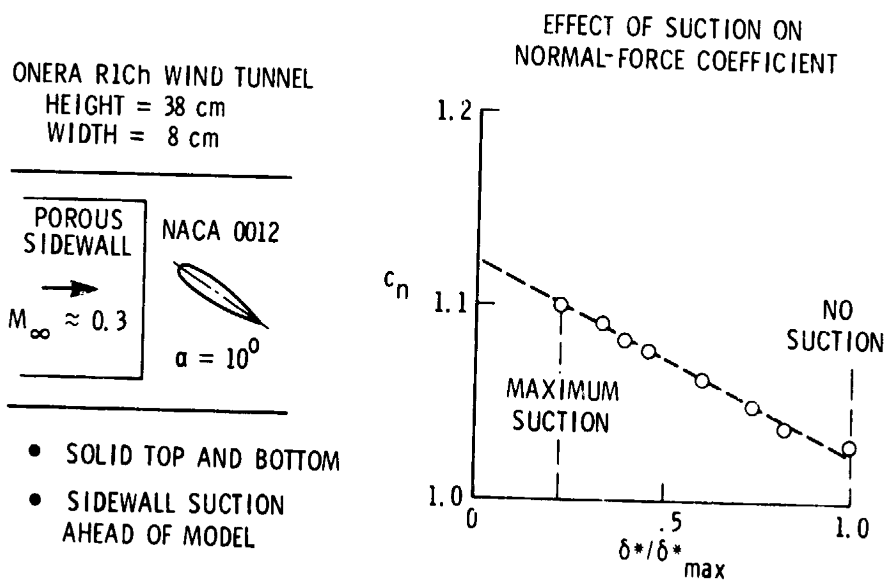

Figure 6.- Effect of sidewall boundary layer on model normal-force coefficient.