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COMPUTER STUDIES OF HYBRID-SLOTTED WORKING SECTIONS WITH MINIMUM INTERFERENCE AT SUBSONIC SPEEDS

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SUMMARY

A series of computations on tunnel boundary-interference effects for hybrid-slotted working sections has been performed using the WALINT code developed at Ames Research Center. The slots were modeled as lines of porosity with linear crossflow characteristics.

The basic shape evaluated was for a rectangular section with height-to-width ratio = 0.835 and its companion in the duplex mode (half-model testing) with height-to-width ratio = 0.6.

A best overall basic configuration was determined with seven slots on each wall with open area ratio on each wall of 17.5%. For both full-span and half-model testing, the optimum solution required closing all but two slots on each of the half-walls parallel to the plane of the wing (equivalent to four slots on the full floor and ceiling).

The results are presented here for the best configurations and are shown to be within the figure-of-merit range of ±0.04 in upwash (δ), and ±0.1 in curvature (δ_1) for the Mach number range 0.6 to 0.85. Blockage effects are shown to be small.

INTRODUCTION

It is well known that work is being done throughout the aerodynamic testing community to advance the state of the art in wind tunnel testing through the use of advanced technology test sections. These sections that are being developed incorporate some means of altering the boundary conditions to simulate free-air flow (e.g., ref. 1). It is only necessary to approach the equivalent free-air flow conditions in the wind tunnel to the degree that either the data can be used with confidence or any residual wall interference effects can be corrected. The ideal frame of reference for modulating the flow at the tunnel boundary seems to be a wall that passively produces minimum interference.

In principle, modulation of the flow can be done through localized suction and introduction of auxiliary air, or through deforming the walls to allow the inviscid airflow to follow the free-air path, or through altering crossflow characteristics of the wall. This last method will only approximate the required airflow, since to match a free-air flow field, some portion of the tunnel flow will require inflow when the pressure difference across the wall is forcing outflow, and vice versa.

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The purpose of this paper is to report on the results from a numerical study which was aimed at identifying a test section whose boundary interference effects will be minimized with only crossflow resistance as the contributing feature.

TEST SECTION

A hybrid slotted-wall test section was chosen as the basic test section. The section has a semiheight to semiwidth ratio (h/b) = 0.835 with the slots modeled as lines of porosity producing crossflow velocity (v) proportional to the longitudinal perturbation velocity (7). The slot boundary condition is $u = v/R$ where $1/R$ is the constant of proportionality. As R approaches 0, the condition approaches that of a solid wall. As R increases to a large number, the condition approaches that of an ideal slotted boundary having no pressure loss through the slot.

Slot spacing, slot width, and R were allowed to vary laterally. The goal was to arrive at an optimum slot configuration that would minimize classical upwash interference (δ) and curvature (δ_1) for large lifting models. Two types of test installations were investigated. These were the basic configuration with h/b = 0.835 for testing full-span models and the duplex equivalent of h/b = 0.6 resulting from testing floor-mounted half-span models. The study assumed that it was permissible to alter slot characteristics from one test-section configuration to the next (e.g., covering up slots and/or changing of R). The basic tunnel geometry derived contains seven slots, symmetrically distributed for a total of 17.5% open area on each wall. In the basic test-section configuration (fig. 1) three of the slots were closed on the floor and the ceiling. The spacings and openings for the optimum wall selected are presented in table 1. The optimum duplex configuration (fig. 1) contained the same number of slots on each wall. The duplex spacing and openings are presented in table 2. The candidate optimum configurations were evaluated for solid and wake blockage, ε_s and ε_w.

COMPUTATIONAL PROCEDURE

The WALINT code (ref. 2) was used for the study. In addition to the reported lift interference correction, the code can also compute solid and wake blockage corrections. In this case, the model is simulated by a distributed set of doublets to represent volumes, and sources to represent wakes.

The underlying assumptions employed in the code are: linear, compressible small-perturbation flow, infinite length test section of constant area, and linear boundary conditions. Flow through a slot is modeled as being proportional to pressure drop through the slot.

MODELS

Interference due to lift was screened using two lifting lines having 28° and 50° of sweep (Λ), respectively. Both lines spanned 0.7 of the tunnel width and were idealized as distributed point-loadings (20 over the span) to approximate an elliptical distribution. Coordinates and normalized lift distributions are shown in table 3.

Solid blockage interference was assessed using an idealized model whose overall length was 0.7 of the test section width (equal to the wing span). The body was elliptical for the first 10.7%, followed by 67.9% of cylindrical section, and concluding with 21.4% of elliptical afterbody. This results in a model volume

$$V = 6(\text{blockage})\left(\frac{h}{b}\right)b^3 = \frac{0.38475}{[\text{Fineness Ratio}]^2[h/b]}$$

As in the case of the lifting line, the body was idealized as distributed volume elements (doublets) with the streamwise coordinate system (X) centered at the midpoint of the body. Normalized volume distribution for the body is presented in table 4. The following equations are derived from reference 3.

Solid blockage velocity ratio is then:

$$\frac{u_s}{U_\infty} = \frac{(\text{Volume})\varepsilon_s}{\beta^3 b^3} \qquad \text{(e.g., eq. 5.22)}$$

Wake blockage interference was computed using a single source located at the center of the body (X = 0).

Wake blockage velocity ratio is then:

$$\frac{u_w}{U_\infty} = \frac{C_D S \varepsilon_w}{\beta^2 b^2} = \frac{4C_D S(h/b)\varepsilon_w}{\beta^2 C} \qquad \text{(e.g., eq. 5.53)}$$

where C_D is wake drag coefficient, S is wing reference area, and $C = 4bh$ is test-section area.

FIGURE OF MERIT

Upwash

The induced angle of attack ($\Delta\alpha$) at any point in the field due to upwash interference is:

$$\Delta\alpha(\text{degrees}) = \frac{180SC_L\delta}{4\pi bh} \qquad \text{(e.g., eq. 3.9)}$$

This can be rearranged by substituting the definition of aspect ratio ($\mathcal{R}$) and defining wing span/test-section width = σ. The result is:

$$(\text{degrees}) = \frac{180\sigma^2 C_L\delta}{\pi(h/b)\mathcal{R}}$$

As reported in reference 4, the most stringent requirement for $\Delta\alpha$ is $\pm 0.01°$ which produces a ΔC_D of 0.0001.

For a transport model of $AR = 12$ and sized such that $\sigma = 0.7$ in the full-span test at $C_L = 0.6$ where $h/b = 0.835$, $\Delta\alpha = 1.68\delta$. To limit $\Delta\alpha$ to 0.01° requires $\delta = 0.00595$. Since some angle-of-attack correction may be permissible, a δ value of 0.04 which is equivalent (for this case) to $\Delta\alpha = 0.067°$ was chosen.

Curvature

The rate of change of the induced angle over the model chord (c) is:

$$\frac{d\Delta\alpha(\text{degrees})}{dX/c} = \frac{cSC_L(180/\pi)\delta_1}{8\beta bh^2} \qquad \text{(e.g., eq. 3.9)}$$

which can be rearranged to:

$$\frac{d\Delta\alpha°}{dX/c} = \frac{\sigma^3 C_L(180/\pi)\delta_1}{2\beta(ARh/b)^2}$$

As reported in reference 4, the most stringent requirement is $\Delta\alpha = \pm 0.03°$ over the model chord. For the conditions previously assumed and at a reference Mach number of 0.8,

$$\frac{d\Delta\alpha°}{dX/c} = 0.09787\delta_1$$

Limiting the angle change over the chord to 0.03° results in $|\delta_1| \leq 0.306$.

For this study, a value of $|\delta_1| \leq 0.1$ was chosen on the basis of limiting the upwash correction at the tailplane to about 0.025°.

Blockage

A figure-of-merit for blockage was not used in the screening of configurations. In general, since the goal was to reduce both δ and δ_1 to a low level, some small blockage was expected. If a figure-of-merit is to be used for blockage, it should be based on buoyancy due to blockage. For example, in reference 3, the relation:

$$\Delta C_{D\ \text{buoyancy}} = \frac{\text{Volume}(10)}{SL(M)(5 + M^2)} \cdot \frac{dM}{dX/L}$$

is given (L = model length).

Converting this to velocity change over the length of the reference body chosen (Δu) results in:

$$\Delta C_{D\ \text{buoyancy}} = \frac{2\ \Delta u(\text{Volume})}{U_\infty SL} = \frac{4.373(\text{blockage})(h/b)\Delta u AR}{U_\infty}$$

It should be noted that $\Delta u/U_\infty$ is proportional to blockage which means that ΔC_D buoyancy varies as $(\text{blockage})^2$.

The basic test section with $h/b = 0.835$, $AR = 12$, and blockage = 0.01 leads to:

$$\Delta C_{D\ \text{buoyancy}} = \frac{0.438\ \Delta u}{U_\infty}$$

RESULTS

General

Although several configurations were evaluated, only the results for those deemed best are shown here. The results for the other cases investigated gave similar trends and results to those presented in reference 2 ($h/b = 1.0$ and $h/b = 0.5$). One of the significant results of the reference 2 study was the ratio of side-wall open area (at constant R) to top and bottom-wall open area required to minimize the spanwise variation of lift interference for large models which was on the order of 3 to 8:1. This is more properly represented as the effective open area ratio (EOR) defined by:

$$EOR = \frac{R_{side(\%open)}\,(h/b)}{R_{top(\%open)}}$$

For the basic test section ($h/b = 0.835$) with $R_{side} = 15$ and $R_{top} = 7.5$, EOR = 2.92 and for the duplex test section ($h/b = 0.6$) with $R_{side} = R_{top} = 15$, EOR = 2.1. These test sections were established as best overall on the basis of the figure-of-merit used. These sections are formed from the basic geometry by appropriately covering up slots in the walls parallel to the plane of the wing. Additionally, the best solution found for the basic test section required changing the R of the slots in these walls from $R = 15$ to $R = 7.5$ (the alternative would be to halve the width of those slots).

Results are presented for the basic test section, $h/b = 0.835$, with both $R_{side} = 15$ and $R_{top\ and\ bottom} = 7.5$, and for an alternate condition with $R = 15$ on all walls (EOR = 1.46). The alternate is attractive because it may be a simple matter to just cover up a slot as opposed to one half of a slot or changing R of a slot.

Results are also presented for the duplex test section, $h/b = 0.6$, with $R = 15$ for all walls. All results shown for lift interference are for 28° swept and/or 50° swept lifting lines that span 0.7 of the width of the test section ($\sigma = 0.7$).

Lift Interference

Basic test section- The effects of R for the basic test section at Mach number 0.8 are presented for upwash and for curvature in figures 2(a) and 2(b), respectively. For comparison, results are shown for $R = 6000$ which corresponds to an $R/\beta = 10{,}000$ at Mach number 0.8. In reference 2, $R/\beta = 10{,}000$ was shown to effectively represent the ideal-slot boundary condition (no pressure drop through the slot).

Recalling that the figure-of-merit for δ was 0.04 and for δ_1 was 0.1, it is seen that δ is satisfied for the basic configuration, very nearly satisfied for the alternate (R = 15), and clearly not satisfied for the ideal-slot configuration (R = 6000).

As for curvature, δ_1 is satisfied for all values shown, but is best for R = 15 on all walls. A comparison of the two figures shows that either δ or δ_1 can be improved at the expense of the other.

The effect of Mach number on both δ and δ_1 for $\Lambda = 28°$ is shown in figure 2(c) for the basic test section. In the Mach number range 0.6 to 0.85, the variations in δ and δ_1 remain relatively constant over the span of the lifting line and the levels stay within the figure-of-merit ranges.

Duplex test section- Upwash and curvature for both lifting lines at Mach number 0.8 for the duplex test section are shown in figure 3(a). Both δ and δ_1 values are well within the figure-of-merit ranges.

The variation of δ and δ_1 with Mach number over the range from 0.6 to 0.85 is presented in figure 3(b) for the $\Lambda = 28°$ lifting line. All values are within the figure-of-merit ranges and the trends are orderly with Mach number (increasing with increase in β).

Blockage

Solid blockage- Solid blockage results are shown in figure 4 for both the basic and the duplex test sections. For the basic test section, the maximum ε_s at any station along the model for a 1% blockage at Mach number 0.8 is -0.0165 which is equivalent to an induced velocity of $-0.0030U_\infty$. The alternate test section value is not materially better. The total gradient over the length of the model is approximately $0.0043U_\infty$ which is significant enough to warrant a buoyancy correction.

The corresponding values for the duplex test section at Mach number 0.8 are essentially identical ($-0.0030U_\infty$ and $0.0048U_\infty$, respectively). The same conclusion holds that a buoyancy correction due to solid blockage is needed.

Wake blockage- Wake blockage results for both the basic and duplex test sections are presented in figure 5. The equation for u_w/U_∞:

$$\frac{u_w}{U_\infty} = \frac{4C_D(S/C)(h/b)\varepsilon_w}{\beta^2}$$

can be rearranged by noting that $C = 4bh$, and the span of the lifting model is $2(0.7)b = 1.4b$. Substituting this result gives:

$$\frac{u_w}{U_\infty} = \frac{C_D(1.4)^2\varepsilon_w}{\beta^2 AR}$$

Assuming for the reference model, $C_{D\ wake} = 0.015$ and $AR = 12$, at Mach number 0.8, $u_w/U_\infty = 0.0068\varepsilon_w$.

The maximum value of ε_w for either test section is -0.018, which corresponds to an interference velocity of $-(0.0001)U_\infty$ which is negligible.

REALISM OF CROSSFLOW RESISTANCE, R

The foregoing analysis (to be applicable to the real world) depends, in part, on the crossflow resistance (R) values determined being achievable and effectively constant with wall differential pressure. A maximum of $R = 15$ is required.

The following information is offered as verification that the values are achievable. As reported in reference 2, the effective R of the baffled slots of the Ames 11- by 11-Foot Transonic Wind Tunnel has been determined to be $R = 19$. In reference 5, an evaluation of the crossflow characteristics of the AEDC 4T tunnel shows R = constant for $\Delta C_p = \pm 0.08$, and that at Mach number 0.7, $\delta_o = 0$, which corresponds to $1/(1 + \beta/R) = 0.447$, occurs with porosity at 3.685%. This results in $R = 0.577$. Converting this to a 100% porous slot that is comprised of holes results in an R value of 15.67 for the slot. Furthermore, in reference 5, the argument is made for the independence of R with Mach number over the transonic range. This is the same result that is shown in reference 6 for the slotted-wall geometries of both the Ames 2- by 2-Foot and the 11- by 11-Foot Transonic Wind Tunnels. Thus, the expectation is that up to $R = 15$ is achievable for slots which are more properly characterized as lines of porosity.

It is not necessary that R be constant over a wide range of pressure differential for the theory to be applicable. All that is required is sufficient local linearity. It is conceivable that higher-order character may be better from the standpoint of reducing δ at a given δ_1, or vice versa.

CONCLUDING REMARKS

The results of this study show that a slotted test section of slots with constant crossflow characteristics can be defined which has a low level of lift interference with small-to-moderate blockage buoyancy effects. The results of this study should serve to heighten the interest of those contemplating:

1. Building a new transonic wind tunnel or test section,

2. Modifying existing test sections to reduce wall interference, or

3. Incorporating active wall technology to existing test sections.

This study has all the limitations inherent in the linear math model which assumed an infinite length test section of constant geometry. It is recommended that the next step for any interested party would be to entertain a pilot program to develop the required data base for arriving at an optimum geometry. Higher order analyses to determine streamwise variations in R, or even the effect of nonlinear crossflow characteristics, should be of benefit.

The results of this study can serve as an effective guide for the definition of test sections of different h/b ratios.

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TABLE 1.- SLOT COORDINATES FOR OPTIMUM BASIC WALL

b = 1.0		h = 0.835	
Top and bottom walls		Side walls	
Slot center (±Y/b)	Slot width/b	Slot center (±Z/b)	Slot width/b
0.2563	0.05	0	0.0417
.7688	.05	.21395	.0417
		.42795	.0417
		.64185	.0417

TABLE 2.- SLOT COORDINATES FOR OPTIMUM DUPLEX WALL

b = 1.0		h = 0.6	
Top and bottom walls		Side walls	
Slot center (±Y/b)	Slot width/b	Slot center (±Z/b)	Slot width/b
0.2563	0.025	0	0.03
.7688	.025	.1538	.03
		.3076	.03
		.4614	.03

TABLE 3.- NORMALIZED LIFT DISTRIBUTION

28° sweep	50° sweep	28° & 50° sweep	Point lift/total lift
X/b	X/b	±Y/b	
0.01855	0.04171	0.0350	0.063370
.05588	.12513	.1050	.062725
.09310	.20856	.1750	.061430
.13030	.29198	.2450	.059435
.16753	.37540	.3150	.056645
.20475	.45883	.3850	.052960
.24197	.54225	.4550	.048225
.27918	.62567	.5250	.041950
.31640	.70909	.5950	.033430
.35362	.79252	.6650	.019830
			1.0

TABLE 4.- NORMALIZED VOLUME DISTRIBUTION

X/b (upstream is negative)	Volume element/total volume
-0.6672	0.011852
-.62313	.029630
-.5745	.038514
-.375	.12
-.225	.12
-.175	.12
.0	.16
.175	.12
.225	.12
.449	.07704
.54625	.05926
.63437	.023704
	1.0

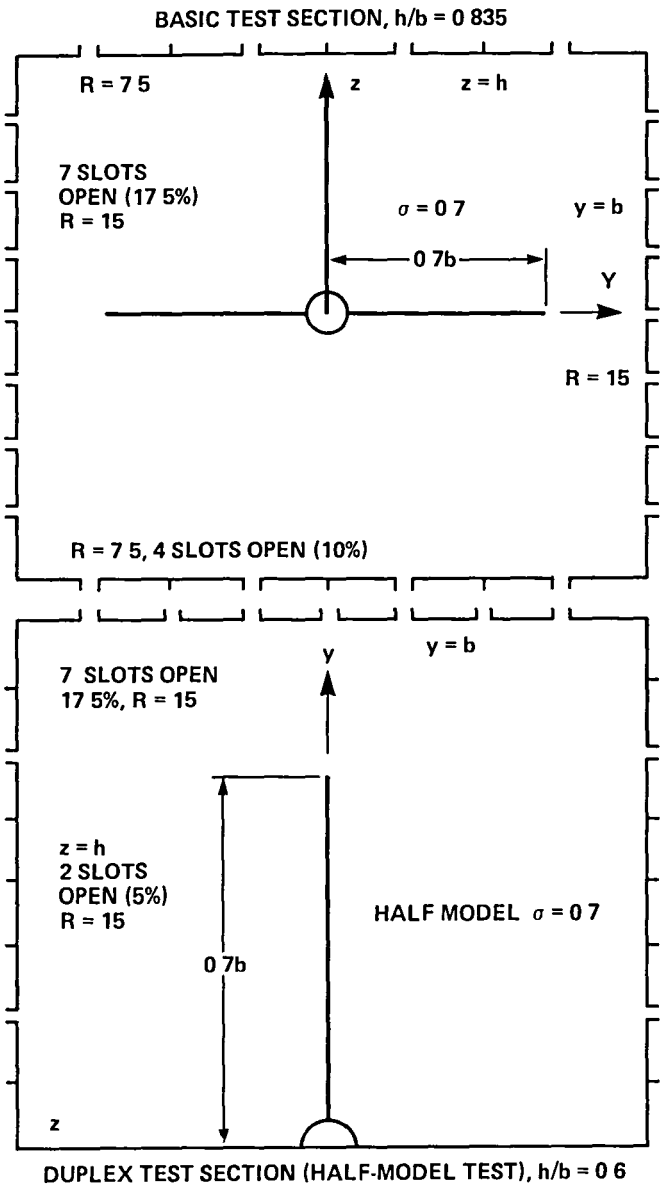
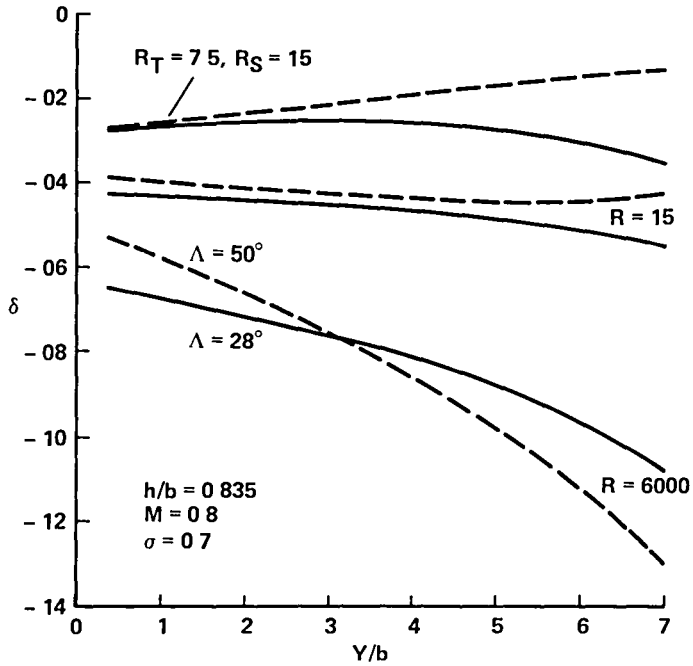
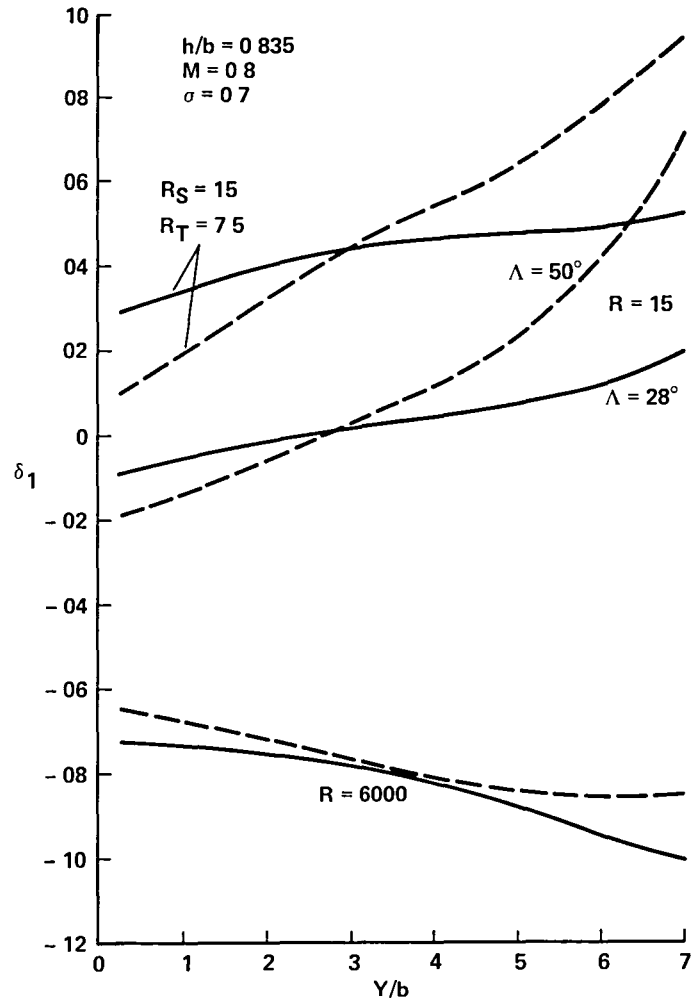


Figure 1.- Test section configurations.



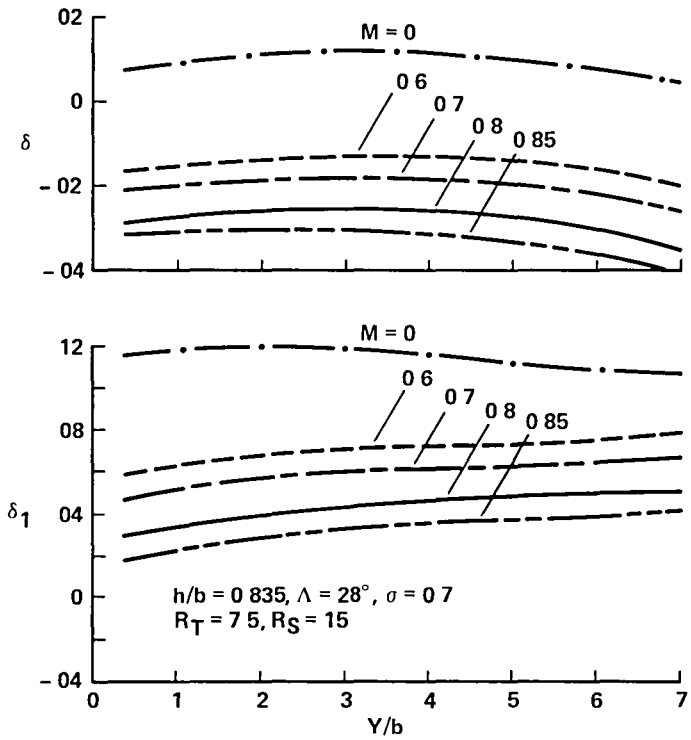
(a) Upwash.

Figure 2.- Basic test section.



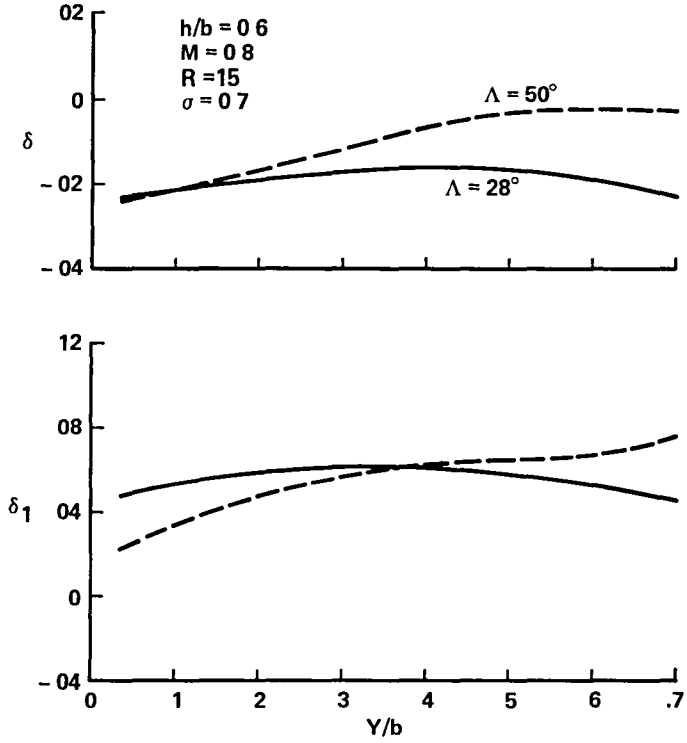
(b) Curvature.

Figure 2.- Continued.

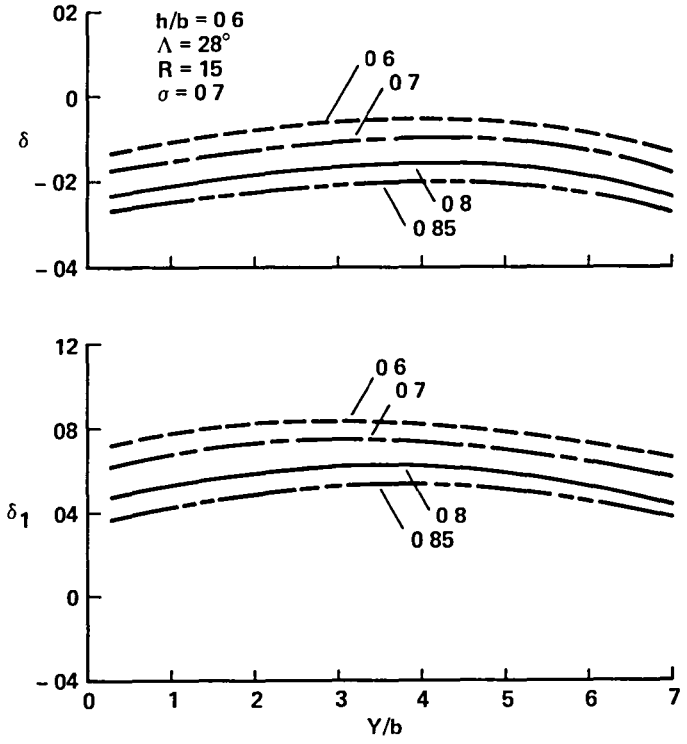


(c) Effect of Mach number.

Figure 2.- Concluded.



(a) Upwash and curvature.



(b) Effect of Mach number.

Figure 3.- Duplex test section.

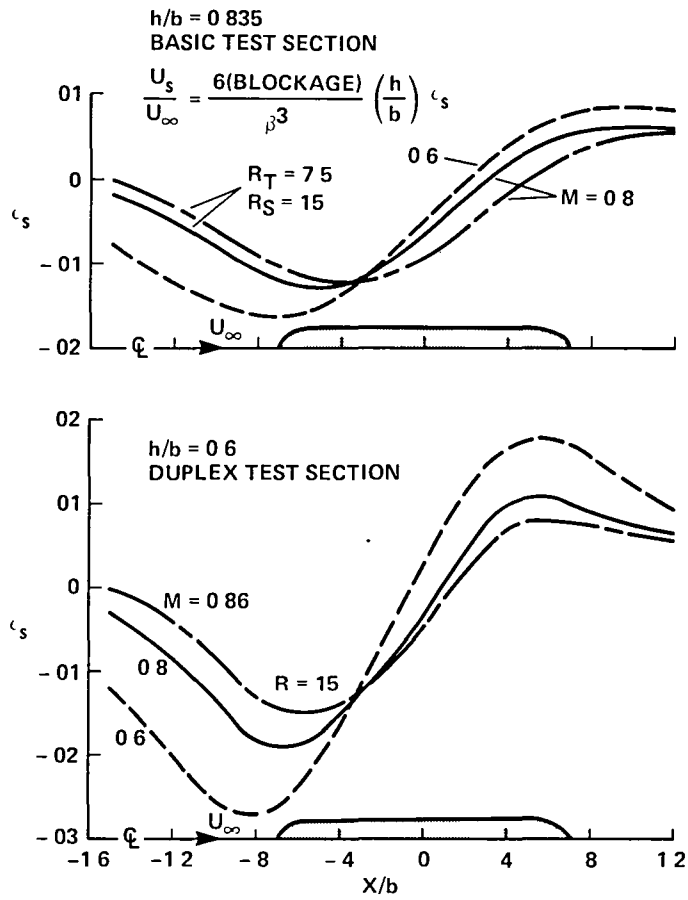


Figure 4.- Solid blockage.

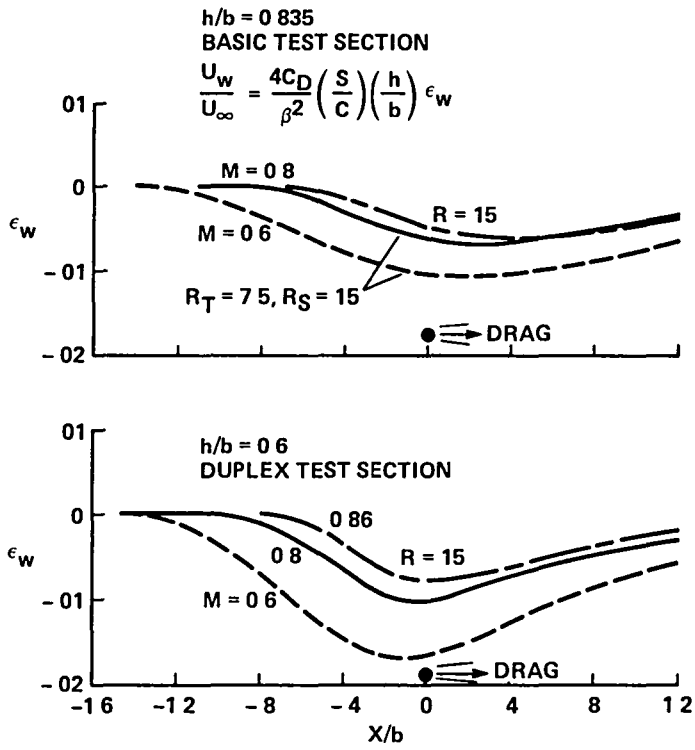


Figure 5.- Wake blockage.

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15 Supplementary Notes

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16 Abstract

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