C_{M2W} (Fig. 2), we see that at all incidences it is maximum when $N=1$ and decreases rapidly to C_{M2C} with increase in N. Finally, from Fig. 3, it is seen that at all incidences $\bar{X}_{C.P.}$ moves forward (toward the nose) when N is even and backward (toward the base) when N is odd, with the maximum backward shift occurring at $N=1$ and maximum forward shift occurring at $N=2$. But, at lower incidence (e.g., at $\alpha=20°$), the $\bar{X}_{C.P.W.} > \bar{X}_{C.P.C.}$ for all N except $N=2$, whereas at higher incidences $\bar{X}_{C.P.W.} < \bar{X}_{C.P.C.}$ for all $N>1$, i.e., $\bar{X}_{C.P.W.}$ shifts toward the nose because of the finite number of waves along the body, before ultimately tending to $\bar{X}_{C.P.C.}$ as N becomes very large.

Conclusions

The results discussed so far pertain to the case when the first half-wave near the shoulder is convex ($\delta>0$). However, the results for $\delta<0$, when plotted as in Figs. 1-3, will be almost mirror images of the corresponding curves for $\delta>0$. Hence, the increase or decrease in C_{N2W}, C_{M2W}, and $\bar{X}_{C.P.}$ will depend primarily on whether the first half-wave is convex or concave. The present study shows that the development of one or two half-waves causes significant changes in normal force, moment, and center of pressure, when the wave amplitude is of the order of 5 to 10% of D_B. However, the development of large numbers of half-waves is not at all critical from a stability point of view.

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Drag of Circular Cylinders at Transonic Mach Numbers

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Introduction

THE static longitudinal forces and moments of aircraft and missiles at high angles of attack can be predicted by semiempirical techniques which combine the lift derived from potential flow theory with a force due to the separation of the viscous crossflow normal to the vehicle longitudinal axis.[1] Evaluation of the viscous term requires an experimentally determined crossflow drag coefficient which may be a function of both Mach number and Reynolds number. Since many vehicle cross sections are at least approximately circular, drag coefficients of circular cylinders over the Mach number range of low-subsonic to supersonic are critical to the semiempirical approach.

The results of numerous wind-tunnel experiments which have measured the drag of bluff cylindrical cross sections are available in the literature (see, for instance, the bibliography in Ref. 1). Most of those tests were conducted at either low subsonic Mach numbers where compressibility and tunnel wall interference can be ignored and/or corrected for, or in supersonic flow where wall interference again becomes tolerable. The results of these experiments have shown that the flow around bluff cylinders at Mach numbers less than about 0.25 is dominated by Reynolds number effects, having either a subcritical or supercritical value of the drag coefficient. At Mach numbers greater than about 2.0 the available data indicate little or no dependence on Reynolds number, and the drag coefficients approach the modified Newtonian value for hypersonic flow.

Data on cylinder drag through the transonic speed range are few. The reported wind-tunnel measurements at high subsonic Mach numbers are influenced to an unknown extent by wall interference.[2,3] An earlier flight test program produced drag coefficients at Mach numbers from 0.5 to 1.3, but with no method to separate the effects of Mach number and Reynolds number.[4] To fill this gap in the data, a wind-tunnel investigation has been conducted specifically to determine drag coefficients for circular cylinders at transonic Mach numbers. Additional data and a detailed account of the experimental procedures are available in Ref. 5.

Experiment and Results

The experiment was carried out in the 0.6-×0.6-m transonic wind tunnel of the NASA Ames Research Center. This facility has an operating Reynolds number range of 0.5×10^6 to 8.7×10^6 per ft, with Mach number independently variable from 0.2 to 1.4.

Stainless steel circular cylinders of four different diameters were tested. Each cylinder completely spanned the test section horizontally, midway between the upper and lower slotted walls. Blockage ratios of cylinder diameter to tunnel height were 0.031, 0.042, 0.062, and 0.084. Surface pressures were measured at nine orifices equally spaced around the circumference. The cylinders were rotated in increments of three degrees to provide a pressure distribution adequate to compute the drag. A drag coefficient C_D based on the projected model area normal to the flow was computed for

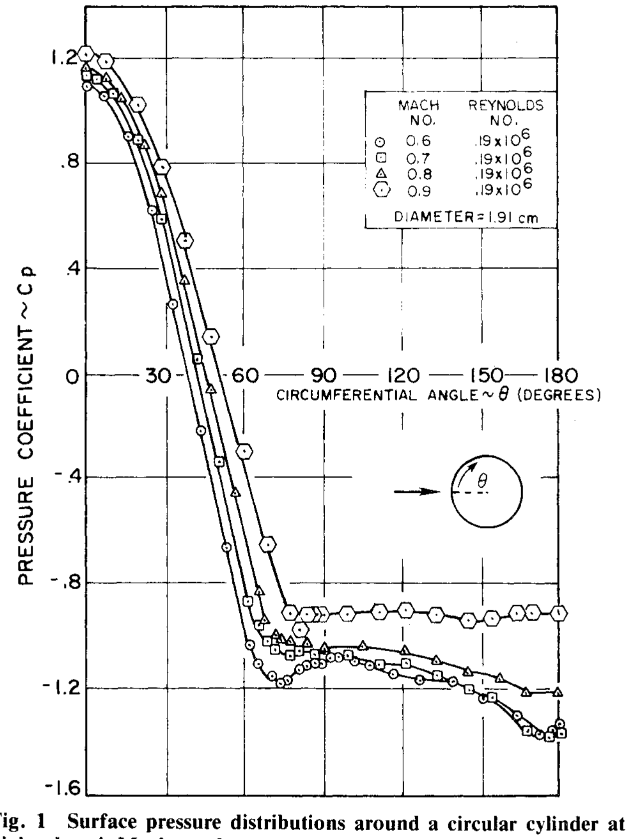

Fig. 1 Surface pressure distributions around a circular cylinder at high subsonic Mach numbers.

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Table 1 Uncorrected circular cylinder drag coefficients

Mach No.	$d^a = 1.91$ R_d^b	C_D	$d = 2.54$ R_d	C_D	$d = 3.81$ R_d	C_D	$d = 5.08$ R_d	C_D	$d = 2.54$ + Roughness R_d	C_D
0.6	.12	1.46	.33	1.47	.33	1.44	.33	1.47	.16	1.36
	.19	1.46	.42	1.49	.44	1.53	.83	1.55	.42	1.41
	.28	1.44	.50	1.58	.56	1.58				
	.33	1.44			.62	1.62				
					.69	1.62				
					.75	1.58				
					.86	1.52				
0.65							.92	1.53		
							1.0	1.52		
0.7	.12	1.54	.17	1.52	.33	1.58	.34	1.61	.17	1.48
	.19	1.54	.33	1.52	.41	1.58	.82	1.68	.42	1.47
	.28	1.56	.42	1.55	.56	1.60	.92	1.63		
	.33	1.57	.50	1.56	.63	1.59				
					.69	1.61				
					.75	1.59				
0.8	.13	1.57	.33	1.51	.33	1.58	.33	1.62	.17	1.46
	.19	1.53	.42	1.53	.44	1.58	.67	1.59	.48	1.46
	.28	1.52	.49	1.54	.56	1.59	.75	1.59		
	.33	1.54			.61	1.60	.83	1.61		
0.9	.12	1.47	.25	1.57	.33	1.54			.17	1.58
	.19	1.45	.33	1.57	.44	1.55			.33	1.53
	.28	1.52								
1.0	.13	1.79	.25	1.72	.33	1.44	.33	1.33		
	.19	1.77	.33	1.72	.44	1.43				
	.28	1.78								
1.06									.33	1.68
1.10	.13	1.67	.17	1.64					.17	1.65
	.19	1.67								
1.20	.13	1.58	.17	1.56					.17	1.57
	.19	1.59	.25	1.56						

[a]Cylinder diameter in cm. [b]Reynolds number × 10^{-6}.

each Mach number-Reynolds number condition. Measurements were made at Mach numbers from 0.6 to 1.2 and Reynolds numbers based on cylinder diameter from 10^5 to 10^6. Table 1 summarizes the uncorrected measured drag coefficients.

Blockage effects on the measurements are analyzed by comparing drag coefficients of all four models at common Mach numbers and Reynolds numbers. The slotted floor and ceiling effectively eliminate any wall interference at a Mach number of 0.6. At Mach = 0.8, the largest model produces a drag coefficient 5.5% greater than the smallest model; drag coefficients of the two smallest models are within 2.0% of each other. At Mach = 1.0 the C_D of the largest two models are considerably less than the smallest two – about 21.0%. For Mach numbers greater than 1.0, measurements at fewer test conditions indicate decreasing wall interference.

Earlier wind-tunnel investigations by Knowler and Pruden[2] and Matt[3] and flight tests by Welsh[4] showed a dip in the C_D vs Mach number curve at a Mach number of about 0.7 to 0.8. In those experiments Reynolds number varied with Mach number so that either could be responsible for the dip. In many cases, the reduction coincided with a Reynolds number in the low-speed "critical" range. In the present tests, Mach number was varied with Reynolds number held constant and the dip still occurs. This indicates that its presence must be solely because of compressibility effects. An examination of Schlieren photographs and pressure distributions reveal two mechanisms which act to reduce the drag as Mach number increases above 0.7. The point of flow separation, which coincides with the shock location, shifts rearward and the pressure in the base region of the cylinder becomes less negative. The variation in base pressure is illustrated in Fig. 1.

Results for the variation of drag coefficient with Mach number are presented in Fig. 2. The range of C_D indicated by the symbols at subsonic Mach numbers is due both to scatter in the data and to variation with Reynolds number. At a Mach number of 0.6, C_D increases by about 10% over a range of Reynolds number of 0.1×10^6 to 0.8×10^6. As Mach number increases, the dependence of C_D on Reynolds number decreases; at Mach = 0.9 and greater, no trend in C_D with

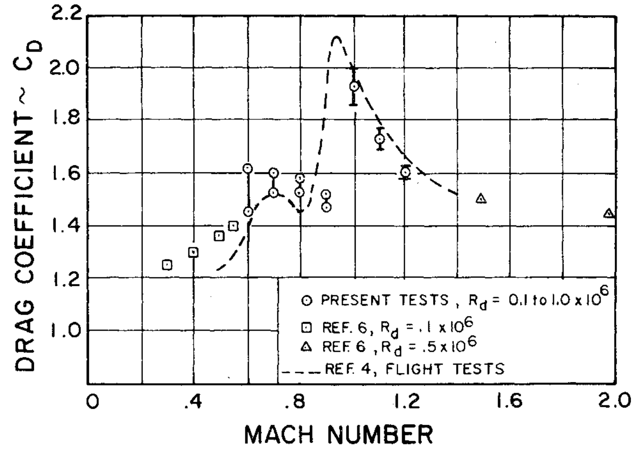

Fig. 2 The variation of circular cylinder drag coefficient with Mach number.

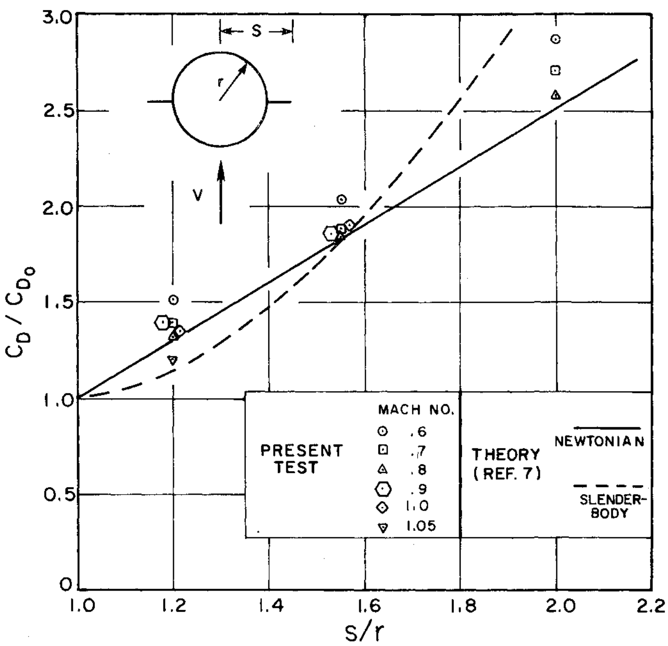

Fig. 3 The effect of wingspan on the drag of a winged-circular cross section.

Reynolds number can be detected in the scatter. For Mach numbers of 1.0 and greater, vertical bars indicate the uncertainty in "correcting" the values to zero blockage. These new data blend smoothly with existing C_D values on both sides of the transonic region.[6]

To investigate the sensitivity of the flow to surface roughness, spherical beads were applied uniformly around the circumference of one of the cylinders such that the roughness height relative to the cylinder radius was 4.0×10^{-3}. This compares to a value of 1.2×10^{-4} for the natural surface finish. At Mach numbers up to 0.9, the added roughness produces a more negative peak in the pressure distribution and a greater pressure recovery over the aft portion of the cylinder. The resulting reductions in C_D vary from about 7.0% at Mach = 0.6 to about 2.0% at Mach = 0.9. At the supersonic Mach numbers, the influence of the added roughness can not be detected.

In applying the force prediction techniques mentioned earlier, the complication of a wing-body combination frequently arises. Methods have been proposed which compute the C_D of such a section based on an "equivalent" circular section.[7] As a check on the validity of this procedure at transonic Mach numbers, three circular cylinders were modified by the addition of strakes running the length of the span. Figure 3 compares the measured C_D with the "equivalent" circular section methods for different values of the ratio of strake height s to cylinder radius r. In the figure, C_{D_0} corresponds to the drag of a cylinder without strakes and both C_D and C_{D_0} are based on the same (equivalent) area. The Newtonian impact theory appears to agree more closely with the test data in the transonic speed range.

Conclusions

Based on a wind-tunnel experiment conducted to measure the drag coefficients of circular cylinders at transonic Mach numbers, several conclusions can be made. The C_D is influenced by Reynolds number at most by only a few percent over a range including the low-speed "critical" region. The influence of a change in relative surface roughness of an order of magnitude also amounts to only a few percent difference. A reduction in the drag coefficient as Mach number increases through 0.7 to 0.8 is caused by the formation and location of shock waves and not by Reynolds number effects, as speculated in previous investigations. Finally, for the s/r ratios tested, the increase in drag due to the wingspan of a wing-body combination appears to be estimated adequately by current theoretical treatments.

Acknowledgment

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Technical Comments

Comment on "LTA Aerodynamic Data Revisited"

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AN excellent review has been given by Curtiss, Hazen, and Putman[1] on the subject of LTA aerodynamics. The classical aerodynamic goal for LTA is the minimization of propulsion power for a given hull volume and a given flight speed. The boundary layer must be assumed completely turbulent because of high Reynolds numbers ($>10^8$) and hull surface conditions. Recently, a methodology has been presented by Parsons, Goodson, and Goldschmied[2] for the automatic synthesis of minimum-drag hull shapes for incompressible axisymmetric bodies of specified volume at given speed. The significant results of these studies is the fact that, for turbulent boundary layers, the volume drag coefficient varies but little for wide variations of the five geometric profile parameters. The "Akron"[3] still yields one of the lowest aerodynamic drag coefficients, at par with the best U. S. Navy Series 58 Model 4176.[4] Parametric studies against fineness ratio, from Hess[5] to Young,[6] substantiate the above.

It can be concluded that means other than body shaping alone are needed to reduce propulsion power. Mention is made by Curtiss, Hazen, and Putman[1] of modern interest in BLC airships, which can reduce friction drag at constant volume with much lower fineness ratios, without allowing concomitant flow separation and high pressure drag. It should be pointed out that a significant attempt to integrate hull design, boundary-layer control, and stern jet propulsion was presented by Goldschmied,[7] on the basis of wind-tunnel tests reported by Cerreta.[8] Further wind-tunnel work was carried out in recent years, with a substantial reduction of the minimum suction flow requirements; these results have been presented by Goldschmied.[9]

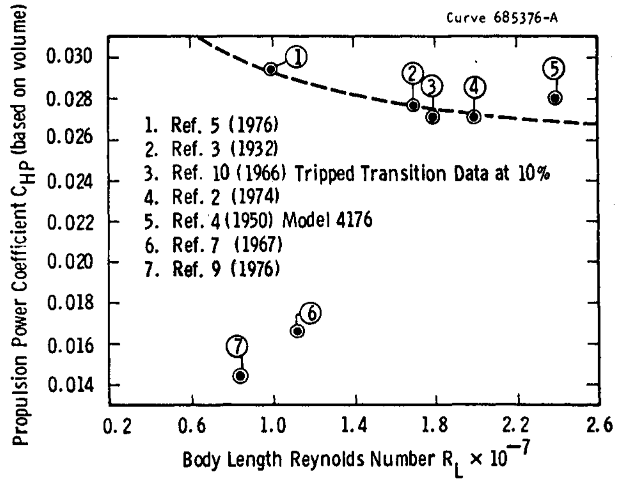

Fig. 1 Propulsion power assessment for all-turbulent vehicles.

A general assessment of the situation can easily be made, as shown in Fig. 1, by plotting the power coefficient C_{hp} (based on volume) against the Reynolds number (based on length). The guidelines are as follows: 1) laminar/turbulent transition is always triggered or assumed at 5% or 10% length from the nose; 2) an additional drag $\Delta C_D = 0.003$ is imposed on all bodies to account for the empennage resistance; c) stern wake-propeller efficiency of 85% is assumed for bodies 1 through 5;

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