Engineering Notes

Three-Dimensional Flow Characteristics about a Curved Circular Cylinder

JEAN C. SURRY*
University of Toronto, Toronto, Canada

THE phenomena described below were encountered during an investigation of the force distribution on cylinders curved in the plane containing the wind vector, at subcritical Reynolds numbers.[1] The results were compared with the cross flow theory (cf. Ref. 2): i.e., the flow about an infinite straight cylinder, inclined at an angle ϕ to the wind, can be described in terms of the algebraic sum of the velocity components tangential ($V \cos\phi$) and normal ($V \sin\phi$) to the body axis; the latter component results in pressures and normal forces on the body proportional to $\sin^2\phi$. It was suspected that this relation was not directly applicable to curved cylinders as has been assumed. Three methods of testing this suspicion are presented.

Static pressures were measured around the circumference of two curved cylinders at several stations of differing angles of inclination to the wind. It was found that in the frontal region the pressures were closely predicted by the $\sin^2\phi$ relation (Fig. 1). However, on the rear portion, the negative pressures were not predictable, being functions of curvature, direction of curvature, and the angle of inclination. These wake pressures showed a high turbulence level but had a constant mean value around the rear circumference.

Flow visualisation with a suspension of lampblack in kerosene and some tuft tests on the same curved cylinders and a straight cylinder indicated the flow mechanisms involved. Some general observations can be made about the flow around the three bodies. The cross flow theory appears valid ahead

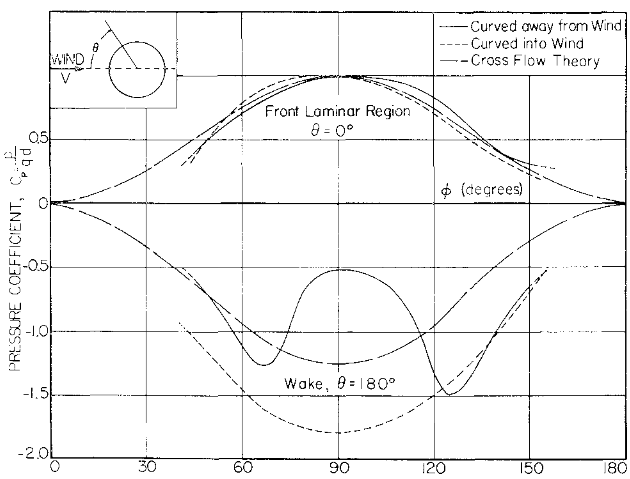

Fig. 1 Pressure coefficient distribution along the front and rear of two curved cylinders.

Received October 1, 1965. Submitted in partial fulfillment of the requirements for the degree of Master of Applied Science in Aeronautical-Astronautical Engineering. The author expresses gratitude to the staff of the Institute for Aerospace Studies at the University of Toronto, Canada and, in particular, to B. Etkin for his guidance throughout this research program.

* Masters's Candidate, Institute for Aerospace Studies; now Aerodynamicist, The de Havilland Aircraft of Canada Ltd.

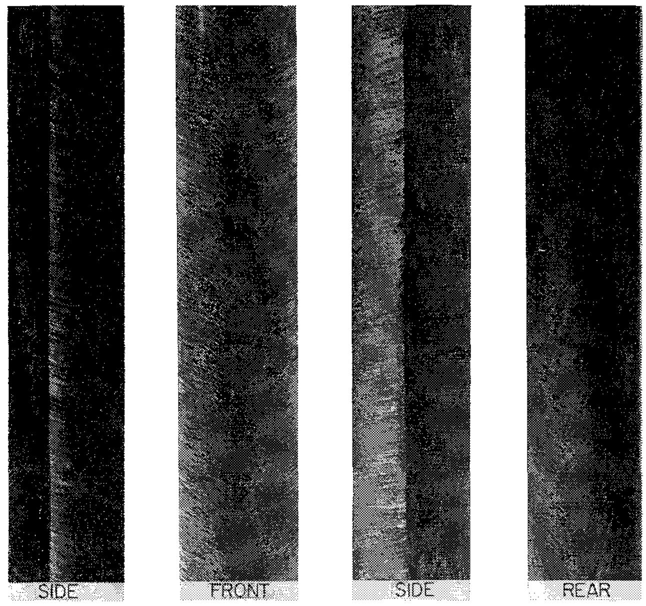

Fig. 2 Four consecutive views of a typical flow pattern around a straight cylinder inclined to the wind.

of separation in the laminar flow region, i.e., the streamlines curved over the surface of the curved cylinders in the same manner as over the straight cylinder inclined at appropriate angles. The azimuthal angle at which separation occurred remained constant except for very low inclinations where it moved rearward. The wakes were three dimensional in all cases since there was a nonzero mean velocity component in the direction of the freestream tangential velocity component.

In detailed structure, the wakes behind the three bodies were not similar. The straight inclined cylinder showed a small mean velocity component in the highly turbulent wake, which was greater just behind the separation lines than in the center (Fig. 2). Figure 3 shows the flow pattern for a cylinder bowed into the wind. The wake appeared to have three regions: just behind the two separation lines the air was almost stagnant, with a tendency to move about the surface on the diametric plane toward the center; in the center of the wake the flow turned and moved parallel to the axis, gathering strength with decreasing angle of inclination. This acceleration away from the portion of the cylinder normal to the flow is in the opposite direction to the pressure gradient predicted by the $\sin^2\phi$ relation and would tend to make the wake pressure even more negative, as seen in Fig. 1. This appears to be due to the shearing effect of the tangential component $V \cos\phi$. For the cylinder bowed away from the wind, the wake had a more complex structure, as shown in Fig. 4. The movement on the surface in the wake was towards the normal portion ($\phi = 90°$), where the fluid bled off downstream (observed by tufts). The direction of the acceleration reflects both the pressure gradients as predicted by the cross flow theory and the postulated shear effect, with a necessary deceleration as the plane of symmetry is approached. Thus, the resulting pressure distribution is modified with both the decreased and increased negative pressures seen in Fig. 1. The most striking feature of the flow about this cylinder was a steady asymmetric cell structure in the wake. This may be the result of vortices shedding alternately from side to side as they move downstream over the body rear surface. Reference

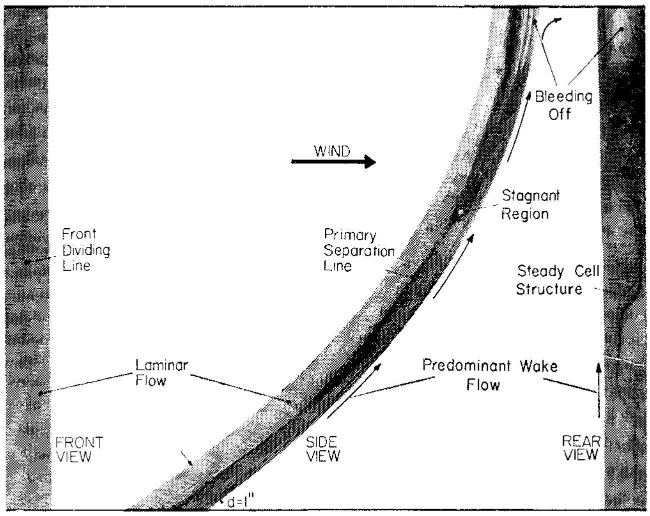

Fig. 3 Three views of the flow pattern around a curved cylinder bowed away from the wind.

3 would indicate that the cylinder was very slightly yawed to the wind, introducing a slight asymmetry in the flow.

Lastly, measurements on flexible curved cylinders (pin-ended at top and bottom in a freestream) gave the local aerodynamic force distribution as a function of ϕ, for various Reynolds numbers and radii of curvature to diameter ratios R/d. Comparison with the prediction for the straight cylinder ($R/d = \infty$), and with the force distribution derived from Fig. 1($R/d = 18$) for the appropriate direction of curvature, shows that the degree of alteration of the wake pressure varies directly with Reynolds number and inversely with R/d (Fig. 5).

The consequence of the poor agreement between the measurement and prediction of the local aerodynamic force on a curved cylinder, is that the cross flow prediction may give a poor estimate of the total drag on such a body. Since the $\sin^2\phi$ relation does not discriminate between directions of curvature, the predicted drag forces are the same for both the curved cylinders tested. This is 21% less than the total drag on a straight cylinder normal to the wind with an equivalent frontal area. However, calculations from the results indicated in Fig. 1 show the drag on the curve away from the wind to be 30% less, whereas that on the curve into the wind is 38% greater. These results are precisely the reverse of the drag forces on hollow half spheres and equivalent circular plates.

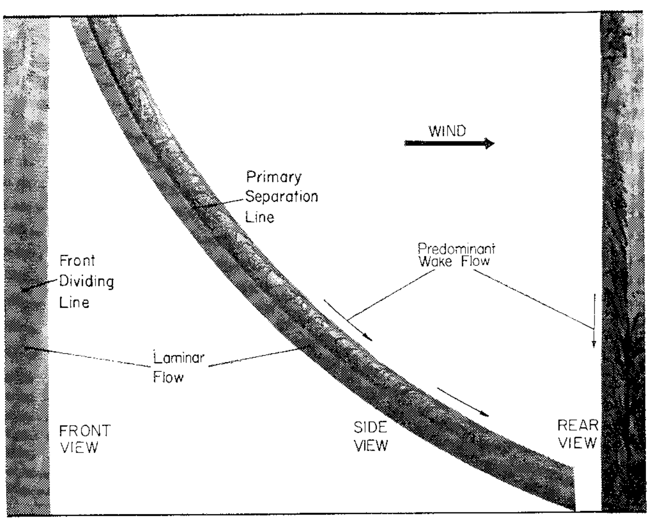

Fig. 4 Three views of the flow pattern around a curved cylinder bowed into the wind.

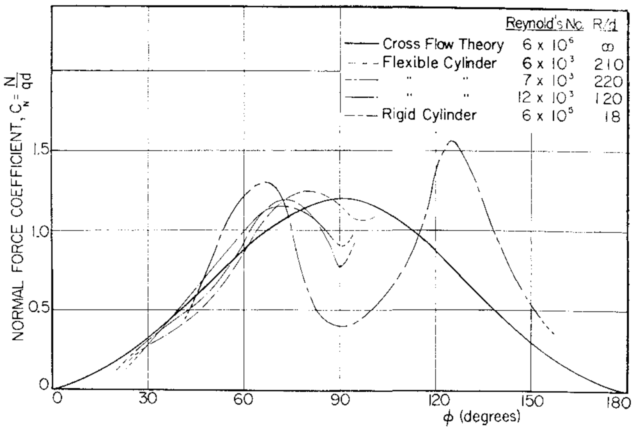

Fig. 5 Normal force coefficient distribution on cylinders curved away from the wind.

It must be concluded that the cross flow relation gives a good description of the flow about curved cylinders, only if the curvature is slight, and that a modification of wake pressures must be considered in estimating the forces on curved cylinders.

References

[1] Surry, J., "Experimental investigation of the characteristics of flow about curved circular cylinders," Insitute for Aerospace Studies, Univ. of Toronto, Toronto, Ontario, Canada, TN 89 (April 1965).

[2] Kuethe, A. M. and Schetzer, J. D., *Foundations of Aerodynamics* (John Wiley & Sons, Inc., New York, 1959).

[3] Rainbird, W. J., Crabbe, R. S., and Jurewicz, L. S., "A water tunnel investigation of the flow separation about circular cones at incidence," National Research Council, Ottawa, Canada, LR-385 (September 1962).

Nomograms for Determining Sonic-Boom Overpressure

Charlie M. Jackson Jr.* and Harry W. Carlson*
NASA Langley Research Center, Hampton, Va.

Nomenclature

C_L = lift coefficient
h = altitude, ft
K_r = reflection constant
l = characteristic length, ft
M = Mach number
P = reference pressure, lb/ft^2
P_0 = atmospheric pressure, lb/ft^2
ΔP = maximum ground overpressure, lb/ft^2
S = wing area, ft^2
W = aircraft weight, lb
β = $(M^2 - 1)^{1/2}$

Introduction

THEORETICAL determination of the sonic-boom overpressure of an aircraft in supersonic flight currently involves application of the flight parameters to a set of nondimensional sonic-boom characteristics. These characteristics can be defined by the configuration geometry and the longitudinal lift distribution as described in Ref. 1. The form of the nondimensional characteristics makes the calculation of

Received September 29, 1965; revision received November 5, 1965.

* Aerospace Engineer, Full Scale Research Division.