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Drag due to a circular cavity in a plate with a turbulent boundary layer at subsonic, transonic and supersonic speeds

Associated software: ESDUpac A7436



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DRAG DUE TO A CIRCULAR CAVITY IN A PLATE WITH A TURBULENT
BOUNDARY LAYER AT SUBSONIC, TRANSONIC AND SUPERSONIC SPEEDS

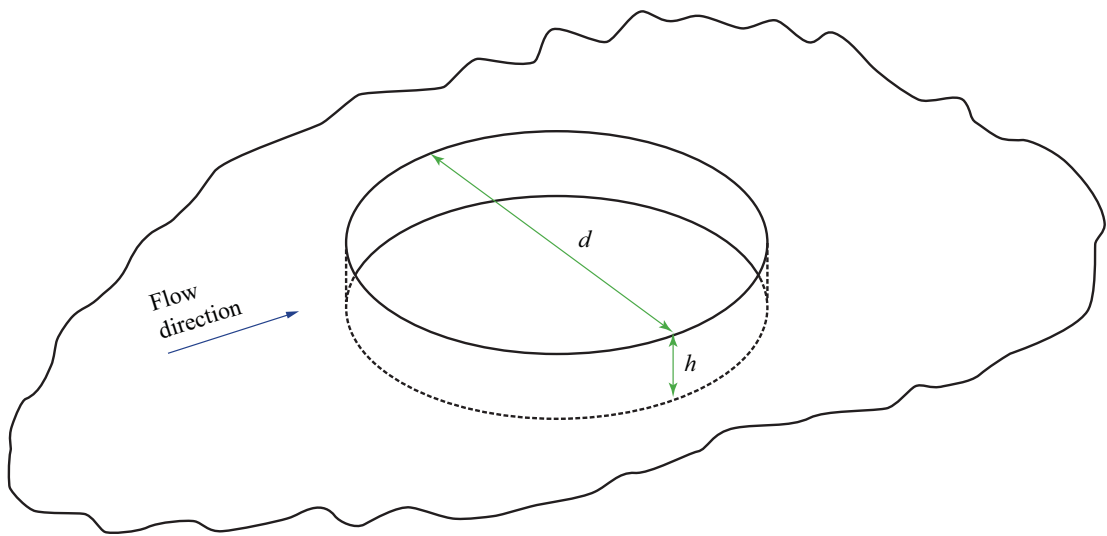
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DRAG DUE TO A CIRCULAR CAVITY IN A PLATE WITH A TURBULENT BOUNDARY LAYER AT SUBSONIC, TRANSONIC AND SUPERSONIC SPEEDS

1. NOTATION AND UNITS

		SI	British
C_D	incremental drag coefficient (defined in Section 3) due to presence of cavity, based on cavity planform area and kinetic pressure at edge of boundary layer		
C_f	local skin-friction coefficient in absence of cavity, based on kinetic pressure at edge of boundary layer		
d	diameter of cavity	m	ft
F, G, H	functions in Equation (3.1)		
h	depth of cavity	m	ft
M_1	local Mach number at edge of boundary layer		
R_d	Reynolds number based on d , local velocity and kinematic viscosity at edge of boundary layer		
δ	local boundary-layer thickness for which local velocity within boundary layer is 0.999 times local velocity at edge of boundary layer	m	ft



Sketch 1.1

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2. SCOPE OF ITEM

Charts described in Section 3 provide a method for estimating incremental drag coefficients for $M_1 \leq 3.0$ due to circular-planform cavities with walls normal to the surface, sharp edges, flat bottoms (no through flow) and of depth/diameter ratios given by $0.04 \leq h/d \leq 1.5$. Some guidance for estimating incremental drag coefficients for shallow cavities ($h/d < 0.04$) is given in Section 4. No systematic drag data are available for circular cavities with rounded or chamfered edges and it should *not* be assumed that such edge modifications are necessarily advantageous.

The charts were derived from experimental data for cavities in a flat plate at zero incidence with a turbulent boundary layer; they apply to airflow with zero heat transfer and are considered valid for cavities of diameter up to about $d = 3\delta$.

Notes on applicability are given in Section 5.

A computer program of the method is provided as ESDUpac A7436 and is described in Appendix B.

3. CAVITIES WITH $0.04 \leq h/d \leq 1.5$

The incremental drag coefficient may be represented by the product

$$C_D = F \times G \times H. \quad (3.1)$$

The functions F (dependent on M_1 and h/d), G (dependent on M_1 and C_f) and H (dependent on M_1 and R_d) are developed in Appendix A and presented in Figures 1, 2 and 3 respectively.

The ranges of the experimental data on which the charts are based are shown in Table 5.1. Outside these ranges the charts should be used with caution. Essentially, Equation (3.1) and the curves presented were derived from tests at subsonic and supersonic speeds reported in Derivations 4, 6 and 8. Derivation 5 presents the results of these tests in a form particularly convenient for use in practice and this form provides the basis of the present Item. Tests in the transonic range between $M_1 = 0.8$ and 1.4 are reported in Derivation 7 and the results have been incorporated in this Item. Equation (3.1) and the curves are substantiated by data from tests at low subsonic speeds reported in Derivations 1, 2 and 3.

In the tests of Derivations 4, 6, 7 and 8 the cavities (of diameter 0.15 m) were located centrally in the circular plate (diameter 0.37 m) of a floating-element drag balance, itself inserted into the wind-tunnel wall. No account was taken of possible effects downstream of the balance plate. Thus, drag coefficients given in this Item represent the streamwise forces on the side and bottom of the cavity plus changes in skin friction on the balance plate due to the presence of the cavity, less the skin friction corresponding to the area of plate removed by the cavity.

Figure 1 shows that at certain values of h/d (e.g. 0.49) maxima occur in the value of F , which are associated with changes in flow pattern within the cavity. Clearly, in designing for low drag, values of h/d which yield high values of F are to be avoided whilst values corresponding to the troughs in F (e.g. $h/d = 0.15, 0.83$) are to be recommended.

Comparison with experiment indicates that C_D from this method is generally accurate to within $\pm 15\%$.

4. SHALLOW CAVITIES WITH $h/d < 0.04$

For shallow cavities of $h/d < 0.04$ Equation (3.1) is not applicable. Instead, it is recommended that a method described in Derivation 4 be used in which the cavity is treated as a combination of rearward- and forward-facing steps of height h and varying angle of sweep. By integrating around the circular planform the following expression (similar to the one developed in Derivation 4) evolves:

$$C_D = 0.85 \frac{h}{d} C_f [(P + Q)_{\text{rearward-facing}} + (P + Q)_{\text{forward-facing}}], \quad (4.1)$$

in which P and Q are defined in and obtained from ESDU 75031.

The lack of reliable experimental data prohibits an assessment of the accuracy of this approach but compared to the accuracy of the data in ESDU 75031 there may be some further loss in accuracy due to the assumptions regarding sweep effects and the interactions between rearward- and forward-facing parts of the cavity wall.

5. NOTES ON APPLICABILITY

The Item is derived from data for circular cavities in a flat plate at zero incidence and for this application C_f may be obtained from ESDU 68020.

The charts would be expected to apply to circular cavities in a parallel circular cylinder in axisymmetric flow provided that lateral curvature effects are small. In practical terms this condition is satisfied if the displacement thickness of the turbulent boundary layer is less than about one per cent of the cylinder radius (see ESDU 68020). The ranges of the experimental data on which the charts are based are shown in Table 5.1.

In flows with pressure gradients the incremental drag coefficient is magnified (*i.e.* amplified or attenuated) compared with its flat-plate value. Some allowance could be made for upstream effects on the drag due to the cavity by using in Figure 2 and Equation (4.1) a value of C_f that is consistent with the pressure gradient. This value might be calculated by means of theoretical methods such as References 10 to 13. Having done this, it would still be necessary to account for the drag magnification that arises downstream. No immediate recommendation can be made on how this can be allowed for, except at sub-critical Mach numbers where Reference 9 provides useful guidance. In Reference 9 the magnification factor was derived with the implicit assumption that the incremental drag coefficient due to an excrescence is based on the kinetic pressure in the free stream. Where the incremental drag coefficient is based on the kinetic pressure at the edge of the boundary layer, as in this Item, and if this value is different from the free-stream value, then in applying Reference 9 the magnification factor must be adjusted accordingly.

TABLE 5.1 Table giving details of experimental data

<i>Derivation</i>	M_1	$\frac{d}{\delta}$	$\frac{h}{d}$	$C_f \times 10^3$	$\log_{10} R_d$
1	0.1	20	0.025 to 1.2	3.75	5.6
2	< 0.1	0.6 1.5	0.10 to 1.48 0.05 to 0.58	} 2.58	4.8 5.2
3	< 0.1	2.9 7.2	0.05 to 1.5 0.025 to 0.6	} 4.18	4.7 5.1
4, 6, 8	0.2 0.8 1.4 2.2 2.8	0.9 approx. 1.0 approx. 1.3 approx. 1.4 approx. 1.7 approx.	{ 0.042 0.083 0.125 0.167 0.25 0.33 0.50 0.58 0.83 1.08 1.33 0.042 to 0.33 only	1.7 to 2.3 1.6 to 2.2 1.4 to 2.1 1.3 to 1.9 1.1 to 1.5	5.4 to 6.3 5.4 to 6.3 5.4 to 6.3 5.3 to 6.2 5.2 to 6.1
7	0.8 to 1.4	1.5 approx.	{ 0.25 0.42 0.50 0.58 0.83 1.08	1.5 approx.	6.3 approx.

6. DERIVATION AND REFERENCES

Derivation

The Derivation lists selected sources that have assisted in the preparation of this Item.

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2. WIEGHARDT, K. Erhöhung des turbulenten Reibungswiderstandes durch Oberflächenstörungen. ZWB ForschBer. 1563, 1942. (Translation available as "Increase of the turbulent frictional resistance caused by surface irregularities", MAP R & T 103, 1946.)
3. TILLMANN, W. Neue Widerstandsmessungen an Oberflächenstörungen in der turbulenten Reibungsschicht. ZWB Unters. Mitt. 6619, 1944. (Translation available as "Additional measurements of the drag of surface irregularities in turbulent boundary layers", NACA tech. Memor. 1299, 1951.)
4. GAUDET, L. JOHNSON, P. Measurements of the drag of excrescences immersed in turbulent boundary layers at Mach numbers between 0.2 and 2.8: circular holes. RAE tech. Rep. 71181, 1971.