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Drag due to grooves in a flat plate with a turbulent boundary layer, at subsonic and supersonic speeds

Associated software: ESDUpac A7528



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THE PREPARATION OF THIS DATA ITEM

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DRAG DUE TO GROOVES IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER, AT SUBSONIC AND SUPERSONIC SPEEDS

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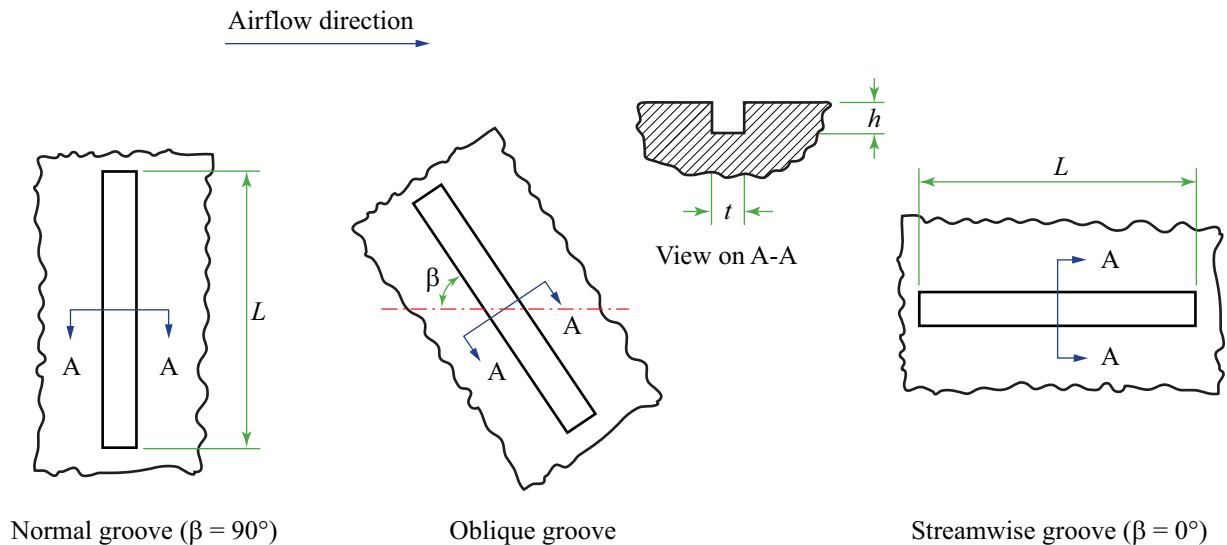
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DRAG DUE TO GROOVES IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER, AT SUBSONIC AND SUPERSONIC SPEEDS

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
C_D	incremental drag coefficient due to groove, based on its planform area ($t \times L$) and kinetic pressure at edge of boundary layer		
C_{DSF}	component of C_D due to skin friction drag on sidewalls of streamwise groove, see Equations (4.2) and (4.3)		
C_f	local skin friction coefficient in absence of groove, based on kinetic pressure at edge of boundary layer, see ESDU 68020		
F	correlation factor for streamwise grooves, see Equation (4.1)		
h	depth of groove, see Sketch 1.1	m	ft
L	length of groove, see Sketch 1.1	m	ft
M_1	local Mach number at edge of boundary layer		
R_h	Reynolds number based on velocity and kinematic viscosity, both at edge of undisturbed boundary layer, and groove depth, h		
R_x	Reynolds number based on velocity and kinematic viscosity, both at edge of undisturbed boundary layer, and distance from virtual origin of boundary layer to centre of groove, x		
t	width of groove, see Sketch 1.1	m	ft
u_τ	friction velocity, $(\tau_w/\rho_w)^{1/2}$	m/s	ft/s
β	angle between major axis of groove and airflow direction, see Sketch 1.1	degree	degree
δ	local boundary-layer thickness for which local velocity in the boundary layer is 0.999 times local velocity at edge of boundary layer	m	ft
ν_w	kinematic viscosity at the wall	m ² /s	ft ² /s
ρ_w	density at the wall	kg/m ³	slug/ft ³

τ_w	wall shear stress	N/m ²	lbf/ft ²
Φ	function in Equation (3.1), see Appendix A		
Ψ	function in Equation (3.1), see Appendix A		



Sketch 1.1 Groove Geometry

2. SCOPE OF ITEM

The charts described in Section 3.1 provide a method of estimating the incremental drag coefficient due to sharp-edged, rectangular section grooves normal to the local airflow direction, with a planform aspect ratio (L/t) greater than 8. For grooves aligned with the local airflow direction, an estimate of the incremental drag coefficient is provided by the recommendations of Section 4.

The Item is based primarily on experimental data obtained at RAE Bedford (Derivation 4) for grooves in a flat wall (corresponding to a flat plate at zero incidence) with a turbulent boundary layer, and is applicable to airflow with zero heat transfer and zero pressure gradient. All the grooves tested had the same depth of 3.81 mm and a groove depth to local boundary-layer thickness ratio of about 0.03 to 0.05 at the test position. The groove geometry covered in the RAE tests was $1 \leq t/h \leq 3$, whilst the test Mach numbers were 0.2, 0.8, 1.4, 2.2 and 2.8.

For the RAE tests the grooves were formed in a circular floating-element drag balance, of diameter 368 mm, set into the wind-tunnel wall. The experimental arrangement was intended to represent two-dimensional flow conditions, the groove ends being formed by the balance housing so that any loads on the ends were not included in the drag measurement. The drag measured was the load on the groove itself plus any changes in skin friction on the balance plate less the skin friction corresponding to the area of the plate removed by the groove, but did not include the effect of drag changes induced downstream of the plate.

Tests from other Derivations (all confined to low speeds) included the drag on the groove ends and so were not directly comparable with the tests reported in Derivation 4. These additional data (Derivations 1 and 2), have however been used in an attempt to quantify the influence of groove ends (Sections 3 and 4) and the effect of oblique flow (Section 5).

Table 6.1 summarises the ranges of experimental data used in the derivation of the methods given in this Item. Outside these ranges the methods may not give satisfactory predictions.

A computer program of the method is provided as ESDUpac A7528 and is described in Appendix B.

3. GROOVES NORMAL TO THE AIRFLOW DIRECTION

3.1 Presentation of Data

The incremental drag coefficient for grooves normal to the flow direction may be represented by the equation

$$C_D = (\Phi - \Psi)C_f. \quad (3.1)$$

Expressions for Φ (dependent on M_1 and R_h) and Ψ (dependent on C_f) are developed in Appendix A from the original RAE correlation (Equation (A2.1) of Appendix A) using formulae given in Derivation 5. The resulting Equations (A2.8) and (A2.9) were then used to derive Figures 1 and 2 respectively. Since all the data available at both subsonic and supersonic speeds are collapsed by the same expression (Equation (A2.1)), it is considered unlikely that there would be any peak in drag coefficient at transonic Mach numbers. Other data supporting those obtained at RAE are given in Derivations 1 and 2. Those applying to grooves with ends indicate that end effects are insignificant for values of L/t greater than 8. For L/t less than 8 end effects become significant, but there are insufficient data to provide any coherent guidance on their magnitude.

Lower limit lines for which the drag given by the charts is zero are indicated on Figure 1 for three values of C_f ; these lines correspond to a calculated roughness Reynolds number ($u_\tau h/\nu_w$) of 10 (see footnote to Equation (A2.1)). For the appropriate values of C_f the charts become less meaningful as these lines are approached, and the drag coefficient should be taken to be zero if a negative value is predicted.

3.2 Accuracy

The ranges of the RAE tests are shown, in terms of R_h and C_f , on Figures 1 and 2. Within these ranges the difference between the experimental values of C_D/C_f , for the more accurate data* and estimates obtained from this Item are contained within a band of ± 2 for the subsonic Mach numbers and ± 1 for the supersonic Mach numbers.

* These were the data for the larger grooves, with consequently larger drag, for which the scatter in the balance measurements was less significant.

4. GROOVES PARALLEL TO THE AIRFLOW DIRECTION

The tests reported in Derivation 4 also involved identical grooves aligned in the flow direction. The drag forces generated by these grooves were comparable with the measuring tolerance of the balance, and the consequent scatter on the results ruled out the establishment of any parametric relationships. However in Derivation 4 it is suggested that the data can be represented by the expression $C_D/C_f = 2h/t$; the implication being that the incremental drag arises very largely from the increased skin friction due to the additional wetted area of the sides of the groove. The above expression obviously applies only to open-ended grooves; for grooves with ends, the end effects will be a predominant factor, even for grooves of high aspect ratio. Indeed, the predominance is such that the deeper grooves can have a considerably higher drag coefficient when aligned in the stream direction than when lying normal to the stream.

Some grooves with ends exhibit a drag peak (Derivation 1) at values of β between 5° and 15° , as discussed in Section 5. It is difficult in practice to determine whether or not a groove is precisely aligned to the local flow, and so it would seem sensible in the drag evaluation process to consider the peak drag as representative of the drag of the groove when aligned in the local stream direction. An analysis of the data in Derivations 1 and 2 then indicates that for grooves with ends C_D may be represented, in low-speed flow at least, by

$$C_D = C_{DSF} + F[C_{D(\text{fore-end})} + C_{D(\text{aft-end})}] \quad (4.1)$$

which assumes the fore-end to be a rearward-facing step and the aft-end to be a forward-facing step, the drag coefficients of which are obtainable from ESDU 75031*. Note that the values thus obtained must be factored to base them on groove planform area. In Equation (4.1) F is a correlation factor obtained from Figure 3 whilst C_{DSF} is a contribution to the drag due to the local skin friction coefficient acting on the sides of the groove, and is given by

$$C_{DSF} = 0.1 \frac{L}{t} C_f \quad \text{for } 8 \leq L/h \leq 10 \quad (4.2)$$

$$\text{and} \quad C_{DSF} = C_f \frac{h}{t} \left[2 - 10 \frac{h}{L} \right] \quad \text{for } L/h > 10. \quad (4.3)$$

These equations for C_{DSF} were derived assuming that the local skin friction coefficient acts over an area equivalent to the side area of the groove less the side area of two regions adjacent to the groove ends where the flow is likely to be separated. The areas of separated flow are assumed to be wedge shaped, with a length to depth ratio of 5:1; this value being derived from studies of flow separation angles over steps.

The foregoing method correlates the available data for $L/h \geq 8$ to within $\pm 3C_f$, but is based on a limited number of test data falling within the range of test conditions $M_1 < 0.1$, $4.6 \times 10^5 \leq R_x \leq 7.2 \times 10^6$, $L/h \geq 8$ and $L/t > 5.4$. Thus the values of F for $L/h \geq 8$ are moderately well substantiated by the available experimental data. For values of L/h less than 8 there are very few data on which to attempt a correlation. It is conceivable that as L/h decreases below 8 there are changes in flow pattern dependent on a number of factors related to the geometry and flow conditions which may lead to non-monotonic variations in drag coefficient with variations in groove geometry (cf. Reference 6 and the Data Item on drag of circular planform cavities ESDU 74036). It is known that large changes in drag coefficient can occur (Derivation 5 and Reference 12) between L/h of 8 and 5 but the sparsity of experimental data prevents any guidance being given on the extrapolation of L/h to values below 8.

* The data in ESDU 75031 are for two-dimensional steps. It is implied in the adaptation of these data to the ends of grooves of small width, that the effects of the ends being of finite rather than infinite extent are contained in the factor F .