

Transonic data memorandum

Calculation of excrescence drag magnification due to pressure gradients at high subsonic speeds

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THE PREPARATION OF THIS DATA ITEM

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CALCULATION OF EXCRESCENCE DRAG MAGNIFICATION DUE TO PRESSURE GRADIENTS AT HIGH SUBSONIC SPEEDS

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CALCULATION OF EXCRESCENCE DRAG MAGNIFICATION DUE TO PRESSURE GRADIENTS AT HIGH SUBSONIC SPEEDS

SUMMARY

Three methods are presented for the estimation of the excrescence drag magnification factor on transonic aerofoils or wings at high subsonic speeds. These take into account the effects of pressure gradient on the development of the turbulent boundary layer downstream of the excrescence and the consequent effects on aerofoil drag. In order of increasing complexity, the methods are as follows.

Method 1, given in Section 4, is a rapid method and requires only a knowledge of the clean surface pressure distribution.

Method 2, given in Section 5, utilises a simple formula and requires a knowledge of flow quantities on the clean surface at the excrescence location and at the trailing edge.

Method 3, described in Section 6, requires the use of a viscous/inviscid computational method.

Verification of the methods, their applicability and their accuracy are discussed in Sections 7, 8 and 9, respectively. Examples of using all three methods to determine the excrescence drag magnification factor are provided in Section 11.

1. INTRODUCTION

Surface imperfections have long been recognised as a source of drag and in the highly competitive field of aircraft design it is important to predict their contribution to aircraft drag with the best possible precision.

Measurements of local drag increments have been made in flows with zero pressure gradient for a variety of excrescences small in relation to the boundary layer thickness. The most extensive collection of these data is that generated by Gaudet, Winter and Johnson at transonic and supersonic speeds (circa 1970 to 1973) and by Pallister and Hutton at transonic speeds (circa 1974). Their work has been reviewed in Reference 1 and much of the data has been collected, correlated with other relevant data and issued in ESDU Data Items (References 2 to 5).

In the case of flows with non-uniform pressure, it is possible to estimate an excrescence drag increment simply by utilising the flow parameters (such as kinetic pressure at the edge of the boundary layer) local to the excrescence, combined with the appropriate zero-gradient excrescence drag coefficient data. However, this disregards any interaction between the excrescence and the development of the boundary layer. Such interaction can be significant, particularly when the pressure gradients are strongly adverse and the boundary layer close to separation (see Reference 6). In these flows the excrescence drag is generally magnified by an amount greater than is accounted for simply by changes in kinetic pressure and other local flow parameters.

This Item describes three procedures for determining the drag magnification for isolated excrescences, taking into account the effects of pressure gradients such as those occurring on aerofoils at high subsonic speeds. It presents data for the drag magnification factor, m_d , which is defined in Equation (3.2). This factor incorporates two effects; namely that due to drag coefficient differences resulting simply from differences between local and freestream values of kinetic pressure, and that associated with changes that the excrescence produces in the local and non-local viscous and inviscid flow fields around the aerofoil.

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The usefulness of m_d is partly due to the fact that, for a given aerofoil, with given flow conditions of Mach number, lift coefficient, Reynolds number and boundary layer transition locations, its value, for a given excrescence location, is effectively independent of the magnitude of the excrescence (within sensible limits).

The first two of the procedures require some knowledge of the aerofoil flow without the excrescence present (termed 'clean aerofoil').

The methods were developed and are generally for use with isolated two-dimensional excrescences, such as those caused by skin joints, slat and flap joints.

The three procedures, given in order of increasing complexity, are:

- (i) **Method 1:** Rapid guide to values of excrescence drag magnification factor for typical pressure distributions on transonic aerofoils.
- (ii) **Method 2:** Calculation of the drag magnification factor using the Nash and Bradshaw (Reference 7) method adapted to compressible flow. To use this method knowledge is required of the pressure distribution and of the boundary layer momentum thicknesses on the clean aerofoil or surface at the excrescence location and at the trailing edge. The method is applicable only to flows without shock waves.
- (iii) **Method 3:** Representation of an isolated excrescence, by an increment in boundary layer momentum thickness, in a viscous/inviscid calculation method.

The viscous/inviscid calculation flow method utilised in Method 3 (and in the derivation of the charts in Method 1) is BVGK (Reference 8), which is a development of the VGK method (Reference 16). In BVGK, the procedures for treating the boundary-layer and wake and their interaction with the inviscid flow differ from those of VGK. Results from BVGK are generally more reliable than those of VGK in cases where the boundary layer is close to separation or has small regions of separation (Reference 16). Extensive separation cannot be treated by either method. In cases where the boundary layer is attached, and not close to separation, the results from the two methods are usually very close. Use of the VGK method, extended so as to estimate excrescence drag, is presented in Reference 14.

2. NOTATION

C_D	section drag coefficient, based on section chord, c , and freestream kinetic pressure, q
ΔC_D	increment in section drag coefficient due to excrescence being present on section, based on section chord, c , and freestream kinetic pressure, q
$(\Delta C_D)_0$	increment in drag coefficient of element of flat plate due to two-dimensional excrescence, based on length c and local kinetic pressure at edge of boundary layer, q_0
$(\Delta C_D)_0'$	increment in drag coefficient of element of flat plate due to two-dimensional excrescence, based on length l and local kinetic pressure at edge of boundary layer, q_0
C_f	local skin friction coefficient in absence of excrescence, based on local kinetic pressure at edge of boundary layer
C_L	section lift coefficient, based on section chord and freestream kinetic pressure
C_p	local pressure coefficient in absence of excrescence, based on freestream kinetic pressure
C_p^*	pressure coefficient corresponding to local sonic flow, based on freestream kinetic pressure
c	section chord
H	boundary layer shape factor ($= \delta^*/\theta$)
$\bar{H}$	boundary layer transformed shape factor (see Equation (6.3))
l	characteristic dimension of excrescence (see Section 3.2)
M	local Mach number in absence of excrescence at edge of boundary layer
M_∞	freestream Mach number
m_d	excrecence drag magnification factor (see Equation (3.2))
q	freestream kinetic pressure
q_0	kinetic pressure at edge of boundary layer at excrescence location, in absence of excrescence
R_c	Reynolds number based on section chord, freestream velocity and kinematic viscosity
R_{c0}	Reynolds number based on c , and local velocity and kinematic viscosity at edge of boundary layer at excrescence location, in absence of excrescence
R_l	Reynolds number based on l , local velocity and kinematic viscosity, both at edge of undisturbed boundary layer
r	recovery factor, represents ratio of frictional temperature increase at the surface to that due to adiabatic compression

t/c	maximum section thickness to chord ratio
U	local velocity in absence of excrescence at edge of boundary layer
U_{∞}	freestream velocity
X	chordwise distance measured from leading edge of section [†]
α	angle of attack
δ	boundary layer thickness in absence of excrescence [†]
δ^*	boundary layer displacement thickness in absence of excrescence [†]
$\Delta\delta_0$	increment in boundary layer thickness representing excrescence [†]
$\Delta\delta_0^*$	increment in boundary layer displacement thickness as defined by Equation (6.2) [†]
θ	boundary layer momentum thickness in absence of excrescence [†]
$\Delta\theta_0$	increment in boundary layer momentum thickness representing excrescence [†]
ρ	local density of air in absence of excrescence at edge of boundary layer
ρ_{∞}	freestream density of air
Suffixes	
<i>clean</i>	denotes value in absence of excrescence
<i>e</i>	denotes value in presence of excrescence
<i>T</i>	denotes section trailing edge conditions
<i>0</i>	denotes conditions at location of excrescence

[†] These quantities are non-dimensionalised with respect to section chord length.

3. DEFINITION OF EXCRESCENCE DRAG MAGNIFICATION FACTOR AND LOCAL INCREMENT IN DRAG COEFFICIENT

3.1 Definition of Excrement Drag Magnification Factor, m_d

The increment in drag coefficient, ΔC_D , due to a small isolated two-dimensional excrescence located at a particular position on the surface of an aerofoil, is the difference between the aerofoil drag coefficient with the excrescence present C_{De} , and with the excrescence absent, C_{Dclean} , with the flow conditions of Mach number, lift coefficient, Reynolds number and boundary-layer transition locations being the same in the two situations. Thus

$$\Delta C_D = C_{De} - C_{Dclean} \quad (3.1)$$

An excrescence could also affect the locations of natural transition but this effect is not considered.

The value of ΔC_D , for a particular combination of aerofoil flow conditions and excrescence type, size and location, is related to the local excrescence drag, expressed as $(\Delta C_D)_0$, which is the increment in drag coefficient experienced by a short element of flat plate due to the same form of excrescence and for which the local conditions of the turbulent boundary layer are the same as those local to the excrescence on the aerofoil. The relationship between ΔC_D and $(\Delta C_D)_0$ defines the excrescence drag magnification factor, m_d :

$$\Delta C_D = m_d (\Delta C_D)_0 \quad (3.2)$$

It should be noted that although the coefficients ΔC_D and $(\Delta C_D)_0$ are based on the same reference length (namely the chord, c), ΔC_D is based on the freestream kinetic pressure, q , whilst $(\Delta C_D)_0$ is based on the local kinetic pressure, q_0 . Thus m_d incorporates two effects; namely that due to drag coefficient differences resulting from q_0 differing from q , and that resulting from the changes the excrescence produces in the non-local viscous and inviscid flow fields around the aerofoil. The latter effect may be considerable, as was demonstrated by Nash and Bradshaw (Reference 7). Since the change in boundary layer growth produced by an excrescence introduces a small change to the effective aerofoil camber, in order to maintain the same lift coefficient as for the clean aerofoil, the incidence of the aerofoil will also be changed slightly. It is found in calculations (see Reference 14) that the value of m_d is largely independent of the magnitude of $(\Delta C_D)_0$, within limits, and the same may be assumed to be the case in practice.

3.2 Local Increment in Drag Coefficient, $(\Delta C_D)_0$

The coefficient $(\Delta C_D)_0$ is the increment in drag coefficient (based on aerofoil chord c , and the local kinetic pressure, q_0) resulting from the excrescence being placed on a short element of a long flat plate, when the flow over the element is equivalent to that local to the excrescence on the aerofoil. The word short here applies to the streamwise length of the element on which the drag acts, and signifies only that (in the absence of the excrescence) the boundary layer parameters may be considered to remain effectively constant over this length (see Reference 17). The equivalence of the local turbulent boundary layer flow over the aerofoil and that over the element of flat plate requires the values of the three dimensionless parameters M_0 , R_{l0} , and C_{f0} to be the same for both flows.

The drag coefficient increment, $(\Delta C_D)_0'$, of an excrescence placed on a short element of flat plate is based on the appropriate characteristic length of the excrescence, l . In order to obtain the value of the

corresponding coefficient based on the aerofoil chord the following equation is applied

$$(\Delta C_D)_0 = (l/c)(\Delta C_D)_0' \quad (3.3)$$

This convention then corresponds to the one adopted in the Items dealing with the drag of three different types of two-dimensional excrescence (References 3, 4 and 5), for each of which the excrescence drag is presented in the functional form,

$$(\Delta C_D)_0' = F(M_0, R_{l0}, C_{f0})C_{f0} \quad (3.4)$$

(Note that in References 3, 4 and 5 the notation used for $(\Delta C_D)_0'$ is simply C_D .)

The data given in References 3, 4 and 5 represent correlations of a large number of experimentally determined drag values. They enable $(\Delta C_D)_0'$ to be found for specific values of the parameters M_0 , R_{l0} and C_{f0} , within relatively wide ranges of these parameters, but the excrescences must be small enough not to extend beyond the wall region of the turbulent boundary layer (see, for example, Reference 18).

A step by step procedure for finding the excrescence drag, making use of VGK and data such as those in References 3, 4 and 5, is given in Reference 14. A corresponding procedure which simply substitutes BVGK for VGK can readily be adopted, if it is required, and this will enable the methods described in Sections 4, 5 and 6 to be extended to provide estimates of excrescence drag, in addition to the excrescence drag magnification factor. For an example of such a procedure, see Section 11.1.

4. METHOD 1: TYPICAL VALUES OF DRAG MAGNIFICATION FACTOR

This method gives a rapid guide to values of excrescence drag magnification factor for typical pressure distributions. Parts (a) of Figures 1 to 6 provide values of drag magnification factor, for a limited range of cases, for two aerofoils representative of design for application at high subsonic speeds. The calculations required were made using BVGK, an improved, semi-inverse version of the viscous Garabedian and Korn's method (VGK) (Reference 8), modified to facilitate an input of increment in momentum thickness, $\Delta\theta_0$, representing the isolated excrescence. This modified method is designated BVGKE and is used for the method described in Section 6. In the calculations the lift coefficient was kept the same as that of the clean aerofoil by allowing the incidence to change. The change in drag due to the excrescence can arise from changes in both the viscous and wave drag components.

4.1 Presentation of Data

The cases considered, for both aerofoils, comprised three freestream Mach numbers, $M_\infty = 0.6, 0.675$ and 0.75 with C_L varied from 0.1 to 0.9 and Reynolds number $R_c = 20 \times 10^6$ (see Section 8 for the effect of Reynolds number). The transition to a turbulent boundary layer was fixed on upper and lower surfaces at $X = 0.02$ and 0.05 , respectively. The data are therefore applicable only to cases where boundary layer transition occurs well forward on the chord on both upper and lower surfaces.

Figures 1 to 3 are for aerofoil RAE 2822, a 12 per cent t/c , mildly rear-loaded and subcritical 'roof-top' type at design conditions.

Figures 4 to 6 are for aerofoil RAE 5230, a 14 per cent t/c , advanced supercritical 'roof-top' type at design conditions, with considerably more aft camber than RAE 2822, resulting in more severe adverse pressure gradients towards the rear of both surfaces.

Both of these aerofoils are typical of transport aircraft sections.

In each figure, part (a) presents the variation of computed drag magnification factor, m_d , with streamwise excrescence location, X_0 , whilst the corresponding clean aerofoil pressure distribution is presented in part (b).

The 'dashed' portion of the curves of drag magnification factor refer to situations where the excrescence is either in the immediate neighbourhood of a strong shock wave or near the trailing edge. In these situations the calculation method is considered to be unreliable. In these cases the 'dashed' line drawn is interpolated or extrapolated using the knowledge that the shape of the curve is similar to the shape of the relevant pressure distribution.

4.2 Use of Data

The user should identify from parts (b) of Figures 1 to 6 the pressure distribution nearest to that of interest and use the corresponding curves of the variation of m_d with X_0 from parts (a) of these figures.

For the figures to be used as presented, the Mach number of interest should be within ± 0.02 of one of the three given M_∞ values. If the location of the excrescence is such that the point of interest is on the 'dashed' portion of the curve, the value of m_d should be used with caution. Furthermore, if the required pressure distribution lies between two given in the figures (*i.e.* at different C_L values) then the value of m_d can be obtained by interpolation. An approximation to m_d can be obtained for a required pressure distribution at an intermediate Mach number also by interpolation provided two suitable pressure distributions from the figures are identified.

If the required pressure distribution does not fall within the limited range of cases given then Method 2 or 3 should be used.

When searching for suitable pressure distributions from parts (b) of Figures 1 to 6 the following should be taken into consideration.

For flows without shock waves (*i.e.* subcritical flow):

- (i) use only pressure distributions without shock waves on any of the surfaces,
- (ii) it is necessary only to match the pressure distribution downstream of the excrescence location on the relevant surface; however, better results are obtained if the overall pressure distributions are similar.

For flows with shock waves (*i.e.* with supercritical flow region):

- (i) if the excrescence location is on the same surface as the only shock wave then the matching of the pressure distributions need only be on that surface,
- (ii) if a shock wave exists on the opposite surface to that on which the excrescence is located then the matching of the pressure distributions needs to be carried out on both surfaces.

When matching pressure distributions with a shock wave present, the shock location and pressure rise across the shock wave should be matched as closely as possible, regardless of excrescence location. If the matching of shock location is not very satisfactory, then compensate this by matching the area of the supercritical flow region as well as possible.

4.3 Derivation of Figures

The calculations to produce the values of m_d in parts (a) of Figures 1 to 6 were carried out using the BVGKE method described in Section 6, with C_L kept constant with and without the excrescence present.

Excrescences were placed independently on each surface for the calculation of m_d at $X_0 = 0.2, 0.5$ and 0.8 on the upper surface and $X_0 = 0.1, 0.5$ and 0.8 on the lower surface. Other excrescence locations were considered, as necessary, to improve the specification of the curves. As in Section 4.1, the locations of boundary layer transition were fixed on the upper and lower surfaces at $X = 0.02$ and $X = 0.05$, respectively.

A nominal value of $\Delta\theta_0 = 0.0001$ was used, which meant that $\Delta\theta_0/\theta_0$ varied between about 0.3 and just less than 1 on the upper surface and between about 0.1 and just less than 1 on the lower surface. From comparisons of m_d from the formula in Equation (5.1), (which assumed that $(\Delta\theta \ll \theta_0)$ and the modified calculation method, BVGKE, it could be deduced that the effect on m_d of the ratio of $\Delta\theta_0$ to θ_0 was negligible, provided $\Delta\theta_0 < \theta_0$. Furthermore, it was found (Reference 9) that increasing $\Delta\theta_0$ to 0.0002 and decreasing $\Delta\theta_0$ to 0.00005 for the extreme cases of RAE 2822 and RAE 5230 had little effect on the value of m_d .

The change of incidence due to keeping C_L constant with and without an excrescence present was less than $\pm 0.1^\circ$ for flows without shock waves and less than $\pm 0.2^\circ$ for transonic flows with shock waves. The change in incidence can itself contribute significantly to the value of m_d when C_D varies rapidly with C_L , as it does in the high C_L cases presented here.

The BVGKE method was required first to solve the clean aerofoil case and then $\Delta\theta_0$ was introduced to represent the excrescence before continuing to obtain a satisfactory convergence. The cases considered here are limited by the program's ability to produce reasonably converged solutions with the excrescence present. It was also found that when the excrescence was in the locality of the shock wave, satisfactory convergence of the solution using BVGKE was not possible, nor could BVGKE produce satisfactory answers when the excrescence was placed close to the trailing edge.

During the preparation of Reference 14 a considerable number of further calculations were made using BVGKE, revealing greater detail in the graphs of m_d against X_0 . (This was possible as a result of the large decreases in computing times and costs since the original calculations were made.) These further calculations showed that in flows without shock waves, the form of the variation of m_d against X_0 was indeed similar to the relevant pressure distribution, as noted in Section 4.1, but with shock waves present the form was generally more complex. In particular, the interaction between the shock and the pressure disturbances produced by an excrescence placed upstream of the shock could lead to either a decrease or an increase in the wave drag, depending on the excrescence location. The interaction can be said to be (respectively) favourable or unfavourable to wave drag generation. This has a counterpart in the work on shock control of aerofoils by means of bumps, see, for example, Reference 15. On wings it would be likely that variations in m_d would be less pronounced than on an aerofoil, as at any flight condition there would generally be portions of the span contributing favourable interference and other portions contributing unfavourable interference. The curves of m_d against X_0 in parts(a) of Figures 1 to 6 were found generally to represent reasonable fairings of the more variable curves obtained from the later, more detailed, calculations, and for this reason their use can be recommended when excrescence drag of wings is of interest.

Two other characteristics of interest were noted from these further calculations of m_d . It was found that the values of m_d obtained from BVGKE could be unduly large when the excrescence location almost coincided with a grid point, as a result of an anomaly in the calculation method. Another point was that irregularities could occur in the detailed curves of m_d against X_0 , in cases when shock waves were present, as a result of the tendency of the computed shock location to 'jump' from one grid point to another on the aerofoil surface, rather than moving smoothly between them. Such irregularities have no physical

counterpart, and are best smoothed out, as has been done in effect in the graphs of Figures 1a to 6a.

5. METHOD 2: CALCULATION OF DRAG MAGNIFICATION FACTOR USING THE NASH AND BRADSHAW METHOD ADAPTED FOR COMPRESSIBLE FLOW

This method applies only to flows without shock waves. For such flows, it may be an improvement on Method 1 and is, of course, applicable also to incompressible flows. For transonic flows with shock waves it is necessary to use Method 3 unless a satisfactory match of pressure distribution is available from Method 1.

An approximate value of drag magnification factor for excrescences in compressible flow is given by

$$m_d = \frac{\rho_T}{\rho_\infty} \left(\frac{U_0}{U_\infty} \right)^{(4.2 - 0.6M_\infty^2)} \left(\frac{U_\infty}{U_T} \right)^{(1 - M_\infty^2)} \left(\frac{\theta_0}{\theta_T} \right)^{0.2} \quad (5.1)$$

The formula is derived in Reference 9 and for $M_\infty = 0$ reduces to the original incompressible Nash and Bradshaw formula. All values on the right-hand side of Equation (5.1) can be determined from the clean aerofoil calculations or measurements. To assist with the enumeration of Equation (5.1), Section 5.1 provides auxiliary equations. The local momentum thicknesses, θ_0 , θ_T , can be determined from a viscous/inviscid calculation (see References 8 or 16, for example) or from a boundary layer calculation using the pressure distribution (References 10 and 11) of the clean surface. Alternatively, measured values of θ_0 and θ_T can be used.

In deriving the formula, certain approximations and assumptions are made (see Reference 9), which are invalid when the excrescence is placed near the trailing edge. It is therefore recommended that the formula should be used only when $X_0 \leq 0.8$.

5.1 Auxiliary Equations

(a) Local Mach number at edge of boundary layer

The local Mach number can be derived from the pressure coefficient, C_p , by using

$$M = \left\{ 5 \left[\frac{1 + 0.2M_\infty^2}{(1 + 0.7M_\infty^2 C_p)^{2/7}} - 1 \right] \right\}^{1/2} \quad (5.2)$$

(b) Local density and velocity at edge of boundary layer

The local density and the local velocity at the boundary layer edge can be expressed in terms of the local Mach number.

The density at the trailing edge is given by

$$\frac{\rho_T}{\rho_\infty} = \left[\frac{1 + 0.2M_\infty^2}{1 + 0.2M_T^2} \right]^{5/2} \quad (5.3)$$