

Transonic data memorandum

VGK method for two-dimensional aerofoil sections Part 6: Aerofoil with simple hinged flaps

**Associated software: VGKSF
(VGK Simple Flaps)**

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VGK METHOD FOR TWO-DIMENSIONAL AEROFOIL SECTIONS PART 6: AEROFOIL WITH SIMPLE HINGED FLAPS

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VGK METHOD FOR TWO-DIMENSIONAL AEROFOIL SECTIONS PART 6: AEROFOIL WITH SIMPLE HINGED FLAPS

1. INTRODUCTION

This Item deals with the flowfield and aerodynamic characteristics of an aerofoil fitted with simple hinged flaps. These may be either leading-edge flaps or trailing-edge flaps, or both types may be present together. The flow calculation method used in this Item for these configurations is VGK, see References 1 and 2. The following conditions apply.

- (i) The freestream speed is subsonic. The flow regime may be inviscid or (more usually) viscous. Regions of supercritical flow and shock waves are catered for, but predictions tend to be less accurate when there are strong shock waves present (*i.e.* when the local Mach number just upstream of the shock exceeds 1.3).
- (ii) Any configuration of aerofoil with flaps deflected should behave like a (cambered) single-element aerofoil, since it is dealt with as such by the VGK method. In particular, there is no modelling of flow through any gap between the main aerofoil element and a flap. Also, the details of the flow near any irregularity in the surface contour (such as a corner or a cavity) produced by the flap deflection, or present in order to permit flap deflection, are not correctly represented.
- (iii) In viscous cases, the flow around the aerofoil configuration must be either free of boundary-layer separation, or have at most only very limited extents of boundary-layer separation. This condition generally limits any flap deflection angle that can be satisfactorily dealt with to a few degrees.

Simple hinged flaps may be utilised for a number of different purposes. They may be used as manoeuvre devices at relatively high speeds (in which case the maximum deflection angles employed would probably only be of the order of 5 deg). They may also be used at relatively low speeds as high lift devices, and then the maximum deflection angles employed could be much higher. In the latter case the present Item would only be suitable for dealing with a limited range of the possible deflection angles.

Compared with the standard use of VGK for flow about an aerofoil (see Parts 1 and 2 of the Items dealing with VGK, References 1 and 2), this Item provides the following additional facilities.

- (a) A program, named ADFLAP, which takes as input the coordinates of the basic aerofoil, the flap hinge coordinates and the flap deflection angles, and then generates coordinates of a shape representing the specified aerofoil and flap combination.
- (b) Modifications to the VGK program which enable flap hinge-moment coefficients to be determined, in addition to the coefficients of lift, drag and pitching moment, and refers these coefficients (as appropriate) to the chord of the aerofoil with the flap or flaps in the undeflected position. These modifications are incorporated into the program VGKSF, which indicates: VGK (method) for an aerofoil with Simple Flaps.
- (c) A batch program (named FLAPSEQ) which facilitates the determination of the aerodynamic characteristics of a particular aerofoil and flap combination corresponding to a number of different deflection angles of either a leading-edge flap or a trailing-edge flap.

Results from using ADFLAP and VGKSF are compared, in a particular example, with results obtained from the ESDU method for hinge moment determination for an aerofoil with a plain control (*i.e.* a simple trailing-edge flap) applicable to low speed flow (Reference 3). The agreement is satisfactory. Further

comparisons are made between results from the present method and experimental data obtained for two supercritical aerofoils, one including simulated deflections of a trailing-edge flap, and the other including a simulation of leading- and trailing-edge flaps each deflected (upwards) through 3.5 deg. These comparisons indicate a range of conditions where agreement is satisfactory.

2. NOTATION

Algebraic notation is printed in italics or has Greek symbols. Notation used in associated computer files is given in Roman type. Notation sequencing is based on the algebraic terms (except where none exists); some file notation therefore appears out of alphabetical order.

Linear quantities made non-dimensional are based on aerofoil chord, c , unless indicated otherwise. Force and pitching-moment coefficients are also referred to the length c .

b_2		rate of change of hinge-moment coefficient with trailing-edge flap deflection, rad^{-1} (note that in Reference 3, the symbol $(b_2)_0$ is used)
C_D	CD	overall aerofoil drag (see Reference 1), with flap(s) deflected when appropriate
C_{HA}	CHA	trailing-edge flap hinge-moment coefficient, H_A / qc_{FA}^2
C_{HF}	CHF	leading-edge flap hinge-moment coefficient, H_F / qc_{FF}^2
C_L	CL	lift coefficient of aerofoil, with flap(s) deflected when appropriate
C_M	CM	pitching-moment coefficient, based on reference point at quarter-chord on the x -axis, positive nose-up, see Sketch 2.1, with flap(s) deflected when appropriate
C_p	CP	pressure coefficient
c	C	chord of aerofoil with flap(s) undeflected, see Sketch 2.1, referred to as basic aerofoil chord
c_f	CF	local skin-friction coefficient
c_{FA}	CFA	trailing-edge flap chord
c_{FF}	CFF	leading-edge flap chord
c_V	CV	aerofoil chord, with flap(s) deflected, as used in VGK calculation, see Sketch 2.1 (set equal to c when flap(s) undeflected)
H_A	HA	aerodynamic moment (hinge-moment) exerted on trailing-edge flap (positive tending to deflect flap downwards) about trailing-edge flap hinge
H_F	HF	aerodynamic moment (hinge-moment) exerted on leading-edge flap (positive tending to deflect flap downwards) about leading-edge flap hinge
	IAFT	control integer, set to 1 if variation of trailing-edge flap deflection angle is to be considered, otherwise set to 0

	IAL	integer denoting number of points nearest to trailing-edge flap hinge removed from specification of lower-surface
	IAU	integer denoting number of points nearest to trailing-edge flap hinge removed from specification of upper-surface
	IFL	integer denoting number of points nearest to leading-edge flap hinge removed from specification of lower-surface
	IFU	integer denoting number of points nearest to leading-edge flap hinge removed from specification of upper-surface
	IFWD	control integer, set to 1 if variation of leading-edge flap deflection angle is to be considered, otherwise set to 0
M	EML	local Mach number (at edge of boundary layer) based on isentropic relations
M_{∞}	EM	freestream Mach number
M_{Lsh}		value of M just upstream of shock wave
q		freestream kinetic pressure
R	RE	Reynolds number based on chord length, c
R_V	REV	Reynolds number based on length c_V
x		chordwise coordinate, with $x = 0$ corresponding to leading edge
z		coordinate normal to x
ξ		non-dimensional x (chordwise) coordinate
ξ_V	X	non-dimensional x (chordwise) coordinate based on length c_V
ζ		non-dimensional z coordinate
ζ_V	Z	non-dimensional z coordinate based on length c_V
α	ALP	aerofoil incidence, <i>i.e.</i> angle between x -axis and freestream direction, positive nose-up, in degrees
δ_{FA}	DELA	deflection angle of trailing-edge flap, positive trailing-edge down (relative to remainder of aerofoil), in degrees
δ_{FF}	DELF	deflection angle of leading-edge flap, positive leading-edge down (relative to remainder of aerofoil), in degrees
Subscripts		
HA	HA	denotes hinge of trailing-edge flap
HF	HF	denotes hinge of leading-edge flap
P		denotes point about which aerofoil pitching moment is calculated

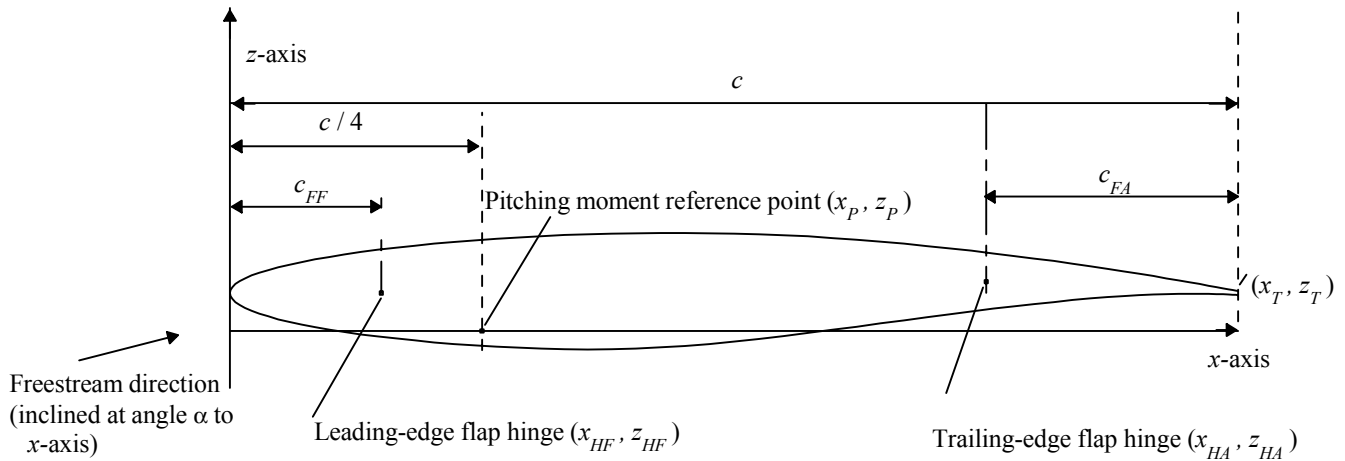
Subscripts

HA	HA	denotes hinge of trailing-edge flap
HF	HF	denotes hinge of leading-edge flap
P		denotes point about which aerofoil pitching moment is calculated

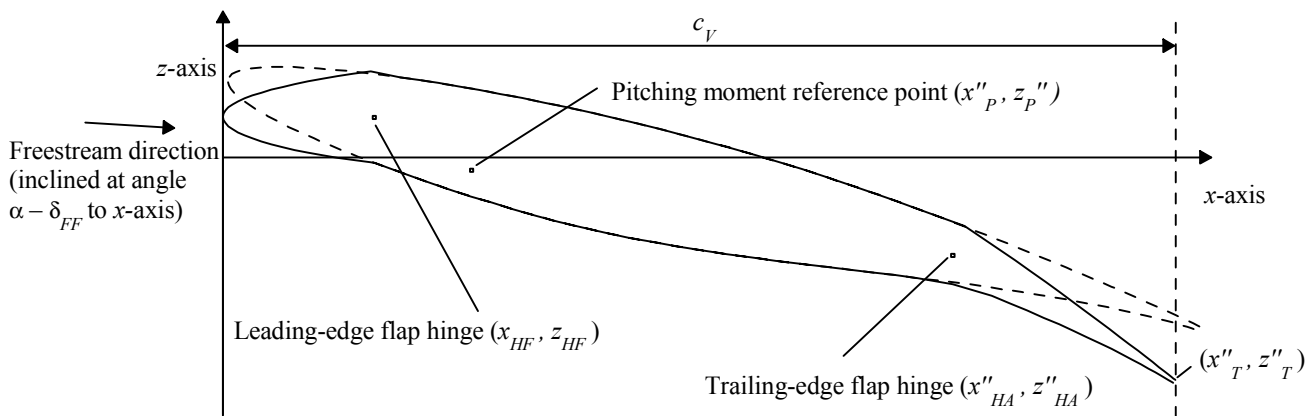
T	denotes value at trailing edge
TL	denotes value corresponding to location of boundary-layer transition on lower surface
TU	denotes value corresponding to location of boundary-layer transition on upper surface

Superscripts

'	denotes value following deflection of trailing-edge flap
"	denotes value following deflection of trailing-edge and leading-edge flap



(a) Basic aerofoil – flaps undeflected



(b) Aerofoil with leading-edge and trailing-edge flaps deflected

Sketch 2.1 Axes and notation for basic aerofoil and for aerofoil with flaps deflected
(Note that flap deflection angles shown in sketch are larger than would be dealt with satisfactorily for viscous flows with VGKSF)

3. EXTENSION OF VGK METHOD TO DETERMINE FLAP CHARACTERISTICS

The use of VGK to deal with an aerofoil with a simulated trailing-edge flap is briefly considered in Reference 1, where some results calculated by VGK for C_L and pressure distributions are compared with corresponding observations on a supercritical aerofoil with a simulated sealed plain control (aileron). In Reference 1 good agreement with observation is demonstrated for those flows which contain at most only very limited regions of boundary-layer separation.

It is apparent that pitching-moment and hinge-moment values determined from VGK should also be close to those observed, under similar conditions, but no such specific comparisons were made in Reference 1; indeed the facility for determining hinge-moment from the VGK solution for pressure distribution is not provided in Reference 1. This Item describes the use of the VGK method extended to include the calculation of hinge-moment coefficient for both leading-edge and trailing-edge flaps. It presents comparisons with values for hinge-moment and other control effects determined from observation and, for low speed flows, for rate of change of hinge-moment with flap deflection obtained from the ESDU method based on correlations of experiment, Reference 3.

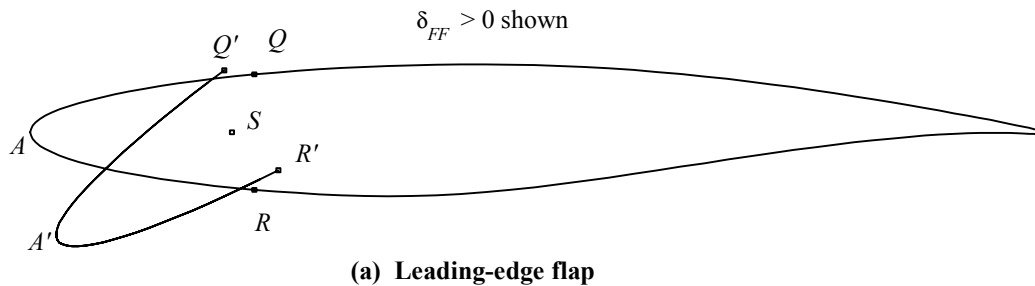
There are two main aspects to the calculation of effects due to flap deflections using the VGK method. The first concerns the representation of the surface geometry with a deflected flap or flaps; the other concerns the extraction of the relevant aerodynamic coefficients including hinge-moment coefficients from the computed pressure distribution. These aspects are dealt with in Sections 3.1 and 3.2 respectively.

3.1 Representation of Surface Geometry With Flap Deflected

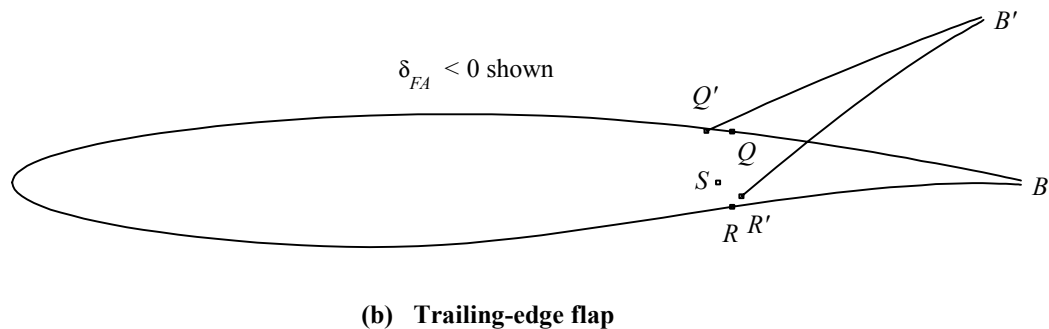
The aerofoil coordinate data that are used as input to VGK must represent the geometrical form of the given aerofoil with a given flap (or flaps) deflected by a particular amount (or amounts). No specific limits to flap deflection angles δ are imposed in this Item, but, as has been noted in Section 1, useful results from the method are likely to be restricted to flap deflections not exceeding a few degrees.

The actual geometric form of any aerofoil provided with a hinged flap may be quite complex. However, in order to utilise VGK, it is necessary for the external form of the aerofoil/flap combination to be capable of being adequately represented as a smoothly cambered single element aerofoil. Thus any gaps present in the actual surface in order to permit flap deflection are considered to be smoothed over (*i.e.* filled in), and any corner present in the actual form is effectively replaced by a smooth curve. The relation between actual flaps and their idealised form is considered in Section 3.1.1. Appendix A describes the use of the programs ADFLAP and ADFLAPSH that calculate geometry representations, as well as the use of VGKSF (the program which embodies the VGK method for an aerofoil with simple flaps).

3.1.1 Idealised flaps considered



S Hinge point
 Q Point on upper surface separating flap from aerofoil
 R Point on lower surface separating flap from aerofoil



In this Item, the x -coordinates of the points Q , S , and R , for a particular flap, are assumed equal

Sketch 3.1

The types of leading-edge and trailing-edge flaps considered in this Item are shown in Sketch 3.1. These are simple idealisations, and refer only to the curves defining the external shape of the aerofoil/flap combination, and thus take no account of any internal mechanism and structure. Any real system is likely to be complex, possibly with flexible seals, and flexible panels, and possibly having linkages replacing simple hinges.

In the idealisation adopted, for a given shape of aerofoil, any flap is defined in relation to the aerofoil with flaps undeflected by

- (a) a hinge point, S , about which the flap element rotates relative to the main aerofoil element, and
- (b) two points, Q on the upper surface and R on the lower surface, which divide the main aerofoil and flap elements.

There are likely to be two cases of main interest. In each of these the points S , Q and R lie on or very

close to a line normal to the x -axis. In the first case the flap is a trailing-edge flap, and S is roughly mid way between Q and R . The second case corresponds to a 'drooped leading-edge', and then the hinge point, S , is likely to be near the lower surface. **In this Item, S , Q and R are assumed to lie on a line normal to the x -axis.**

Referring to Sketch 3.1, deflection of a flap corresponds to rotation of the segment QAR or QBR about the point S . The positions of the segment after deflection are denoted by $Q'A'R'$ and $Q'B'R'$. In simple terms, any finite deflection generally results in a gap or hole on one side of the aerofoil, and a clash or 'digging-in' on the other side. In an actual situation, as opposed to a simple idealisation, the gap might correspond to a cavity or it might be faired smoothly (or nearly smoothly) by the part of the flap or aerofoil that is concealed when the flap is in the undeflected position. In an actual situation, the digging-in might be avoided by cutting back the flap element, or by use of a flexible seal between the flap and the aerofoil.

At this stage it is worth recalling that in using VGK the upper and lower aerofoil surfaces are specified by a number of points (a maximum of 250 points for each). The VGK method utilises these points in the calculation of a conformal mapping of the region outside the aerofoil, and thereby generates a computational grid. The points of this computational grid corresponding to the aerofoil surface generally do not coincide with the specified surface points, but appear as reasonable interpolations between them. What is desired is that, both with and without flaps deflected, the surface points of the computational grid be so located that the computed flow fields and aerodynamic characteristics are adequate approximations of the actual ones. Whether or not this is achieved in any situation can only be established by consideration of a number of examples, such as was done in Reference 1 (principally) for aerofoils without flaps. For aerofoils with flaps, the maximum flap deflections for which VGK is likely to provide reliable viscous flow data are of the order of a few degrees. Inviscid flow data are likely to be satisfactory up to higher deflection angles. For both situations, a suitable representation of the aerofoil geometry with the flap or flaps deflected can be achieved by adopting the following scheme, which is implemented by the program ADFLAP, see Appendix A.

- (a) Where flap deflection results in a gap in the surface (between the flap and main aerofoil), no additional aerofoil surface points are specified to bridge the gap. The numerical procedure that implements the conformal mapping within VGK supplies (in effect) a bridge or interpolation across that gap.
- (b) A clash between the flap and main aerofoil is detected by a test applied to the x -coordinates of the points corresponding to the deflected flap and aerofoil surface. Upper and lower surfaces are considered separately. If the x -coordinates do not give a monotonic sequence, a clash is presumed to have occurred and surface points are removed until no clash remains.
- (c) As a means of controlling the representation of the surface, further points may be removed from the specifications of the upper and/or lower surfaces near the hinge locations as a matter of choice. In general, the more points that are removed in this way, the more gradual is the blend between the deflected flap and the main aerofoil in the consequent VGK representation.
- (d) In representing a deflected leading-edge flap, the coordinates of the flap portion are kept unchanged from those of the undeflected form, whilst those of the main aerofoil are changed, see Sketch 2.1. In other words the flap is considered to be held fixed, and the aerofoil is rotated relative to it. The reason for doing this is a consequence of the sensitivity of the computed flow field parameters to the precise specification of the coordinates near the leading edge. If the coordinates representing the most forward part of the flap/aerofoil combination are changed from those of the basic aerofoil (in the manner that results from either upward or downward deflection of a leading-edge flap), any flow calculated by VGK is generally somewhat irregular and unrealistic near the leading edge.

When representing a deflected leading-edge flap by holding the flap fixed and rotating the aerofoil portion, it is important to note that rotation of the aerofoil portion changes the effective incidence by an amount equal to the leading-edge flap deflection angle. It is necessary to allow for this in specifying and interpreting the value of incidence used in the VGK calculations, which is defined as the angle of the freestream velocity relative to the x -axis. Such allowance is incorporated into the program VGKSF.

A simpler alternative representation of an aerofoil with flaps deflected through small angles (than that described in (a) to (d)) is often satisfactory. In this the x -coordinates of the points specifying the upper- and lower-surfaces are left unchanged, but the z -coordinates are changed so as to constitute a shearing of the undeflected form, see Section 4. This alternative representation is provided by the program ADFLAPSH (see Appendix A). In order to retain similarity with ADFLAP, deflection of a leading-edge flap is again dealt with by deflecting (in this case, shearing) the aerofoil aft of the leading-edge flap.

3.1.2 Geometric parameters relevant to aerofoil with deflected flaps

In this Section the algebraic relations for the various geometric parameters required are listed. The case treated is the general one where both leading-edge and trailing-edge flaps are deflected.

In order to evaluate c_V/c , and the relations between the coordinates of the surface and hinge points in the undeflected and deflected states, the trailing-edge flap deflection is considered to be applied first, followed by that of the leading-edge flap. This has a slight advantage because trailing-edge flap deflection does not affect the coordinates of the leading-edge flap hinge, whereas the reverse is not true, since leading-edge flap deflection is considered to be achieved by keeping the leading-edge flap element stationary, and rotating the remainder of the aerofoil relative to it.

The coordinates of the points on the aerofoil following deflection of the trailing-edge flap are given by the following equations.

If $x > x_{HA}$,

$$x' = x_{HA} + (x - x_{HA}) \cos \delta_{FA} + (z - z_{HA}) \sin \delta_{FA}, \quad (3.1)$$

$$z' = z_{HA} + (z - z_{HA}) \cos \delta_{FA} - (x - x_{HA}) \sin \delta_{FA}. \quad (3.2)$$

For $x \leq x_{HA}$, the points are unchanged, *i.e.* then

$$x' = x, \quad (3.3)$$

$$z' = z. \quad (3.4)$$

In particular the flap hinge coordinates are not changed. The coordinates of the trailing-edge following the deflection of the trailing-edge flap are given by:

$$x'_T = x_{HA} + (c - x_{HA}) \cos \delta_{FA} + (z_T - z_{HA}) \sin \delta_{FA}, \quad (3.5)$$

$$z'_T = z_{HA} + (z_T - z_{HA}) \cos \delta_{FA} - (c - x_{HA}) \sin \delta_{FA}. \quad (3.6)$$

Next consider deflection of the leading-edge flap by keeping points forward of $x' = x_{HF}$ (*i.e.* $x' < x_{HF}$)

unchanged and by deflecting points for which $x' > x_{HF}$, yielding the following relations:

$$x'' = x_{HF} + (x' - x_{HF}) \cos \delta_{FF} + (z' - z_{HF}) \sin \delta_{FF}, \quad (3.7)$$

$$z'' = z_{HF} + (z' - z_{HF}) \cos \delta_{FF} - (x' - x_{HF}) \sin \delta_{FF}. \quad (3.8)$$

If (x', z') are given the values (x_T', z_T') in Equations (3.7) and (3.8), then the results for (x_T'', z_T'') are obtained. In particular,

$$x_T'' = c_V. \quad (3.9)$$

For an aerofoil with a finite trailing-edge thickness, the most aft (*i.e.* the last) point of each of the upper- and lower-surfaces must be considered as a candidate for the point T . The one producing the larger value of c_V is the one selected. Because of the way the mapping which produces the grid is carried out in VGK, it is necessary for the last point of both surfaces to have the same value of x specified. In order for this to be satisfied in the case of an aerofoil with a finite trailing-edge when a finite flap deflection is applied, in the program ADFLAP the surface producing the smaller value of c_V is arbitrarily extended by a straight line passing through its last two (*i.e.* its two furthest aft) points.

Again using Equations (3.7) and (3.8), the coordinates of the trailing-edge flap hinge are

$$x_{HA}'' = x_{HF} + (x_{HA} - x_{HF}) \cos \delta_{FF} + (z_{HA} - z_{HF}) \sin \delta_{FF}, \quad (3.10)$$

$$z_{HA}'' = z_{HF} + (z_{HA} - z_{HF}) \cos \delta_{FF} - (x_{HA} - x_{HF}) \sin \delta_{FF}. \quad (3.11)$$

The location of the pitching moment reference point (*i.e.* the point on the aerofoil about which the pitching moment is estimated) is $(x_P, z_P) = \left(\frac{c}{4}, 0\right)$ before flap deflection. Following deflection of a leading-edge flap of chord less than $\frac{c}{4}$, it is given by:

$$x_P'' = x_{HF} + \left(\frac{c}{4} - x_{HF}\right) \cos \delta_{FF} - z_{HF} \sin \delta_{FF}, \quad (3.12)$$

$$z_P'' = z_{HF} - z_{HF} \cos \delta_{FF} - \left(\frac{c}{4} - x_{HF}\right) \sin \delta_{FF}. \quad (3.13)$$

3.2 Determination of Pressure, Force and Moment Coefficients

In the program VGKSF, prior to the flow calculations being performed, the values of R , ξ_{TU} , ξ_{TL} and α are adjusted from their values corresponding to the aerofoil with undeflected flaps to values which correspond to the aerofoil with deflected flaps.

Once the flow calculations in VGKSF have been completed, a subroutine, named GETCP, is called, the purpose of which is to determine the aerofoil pressure distribution and the lift, drag and pitching moment coefficients. Compared with the standard VGK program, in VGKSF this subroutine is extended so as to determine:

lift and drag coefficients referred to the basic aerofoil chord, c ,

pitching-moment coefficient (also referred to c) about the quarter-chord point of the aerofoil with flaps undeflected, and

hinge-moment coefficients, referred to c_{FF} or c_{FA} as appropriate, for the leading-edge and trailing-edge flaps.

In performing the calculation of hinge-moment coefficients, only the contributions from the pressure coefficients corresponding to the relevant flap region are included. In determining the extent of such a region, the ξ_V value of the hinge point is calculated. It is then assumed that the values of ξ_V of the points separating the aerofoil and flap elements are the same as that of the hinge. For flap deflection angles for which VGKSF is likely to be applicable, use of this assumption should lead to negligible error.

The additional data required by VGKSF are read from a file with the VGK filename extension FIP (denoting flap input). The coefficient values determined by VGKSF are written to a file having the VGK filename extension FOP (denoting flap output), as well as to the files with extensions BRF and FUL. (See Reference 2 for the meanings of the files utilised with VGK.) All force and moment coefficients output by VGKSF are based on c rather than c_V . However, all references to positions on the aerofoil surface (for example where the pressure distribution is given) are presented in terms of the non-dimensional coordinate ξ_V , which refers to the aerofoil with flaps deflected. There are 10 parameters in the file with extension FOP, namely

$$M_\infty, \alpha, \delta_{FF}, \delta_{FA}, C_L, C_M, C_D', C_D'' + C_{D1}, C_{HF} \text{ and } C_{HA}.$$

Here C_D' denotes C_{DV} (*i.e.* the viscous drag coefficient, determined from the momentum thickness of the wake far downstream, see Reference 1) in the case of a viscous run of VGKSF, or C_{DP} (*i.e.* the surface pressure contribution to drag coefficient, see Reference 1) in the case of an inviscid run. C_D'' denotes C_{DV} in the case of a viscous run and is set to zero in the case of an inviscid run. C_{D1} denotes the wave drag coefficient, see Reference 1, Section 3.4.

3.3 Calculations for Several Values of Flap Deflection Angle

A batch file, named FLAPSEQ, is provided to give results for flap effects over a range of values of flap deflection angle, for a particular aerofoil and flap arrangement, at a particular combination of α (or C_L), M_∞ , R , ξ_{TL} and ξ_{TU} . Variations of either leading-edge or trailing-edge flap deflection may be treated. A description of FLAPSEQ is given in Appendix A. If only a few results are required, or if a careful analysis of each flow is desired, it may not be worthwhile to use FLAPSEQ, and then the programs ADFLAP (or ADFLAPSH) and VGKSF may be simply run as required.

4. EXAMPLES OF USE OF ADFLAP AND ADFLAPSH WITH VGKSF

In this Section examples are given of the use of the programs ADFLAP (which generates coordinates of the aerofoil with flaps deflected by rotation) and ADFLAPSH (which performs a similar task, but employs shearing to define flap deflection). The coordinates produced by these programs are then utilised with VGKSF to illustrate the effects of the differences between the two approaches and also the effects of the various degrees of smoothing in the regions near the flap/aerofoil junctions produced by removing points from the surface specifications (see Section 3.1.1). In the examples in this Section, the VGKSF calculations correspond to low speed ($M_\infty = 0.05$) inviscid flow at a fixed incidence of 2 deg. Further calculations, and comparisons with observations, are presented in Section 5, where values of M_∞ up to 0.74 are considered.

4.1 Examples with Uncambered Basic Aerofoil

The aerofoil selected for these examples is the RAE 2822 aerofoil as specified in the file RAE2822.DAT, see Reference 2. Both leading- and trailing-edge flaps are considered to be present, and the flap hinge coordinates are given by:

$$\begin{aligned}(x_{HF}/c, z_{HF}/c) &= (0.2, 0), \\ (x_{HA}/c, z_{HA}/c) &= (0.7, 0).\end{aligned}$$

Three cases are considered, namely $\delta_{FF} = \delta_{FA} = 5$ deg, 10 deg and 15 deg. Figure 1 compares the coordinates generated by ADFLAP and ADFLAPSH for these cases. With the lowest flap deflections the differences between the coordinates are seen to be small, but with the two higher values of the deflections, the differences become more noticeable, especially over the region of the trailing-edge flap. For the highest deflections, flap deflection by rotation almost results in a clash on the lower surface in the sense described in Section 3.1.1.

Comparison of the corresponding pressure distributions found from runs of VGKSF for inviscid, low speed flows at fixed incidence are shown in Figure 2. It is seen that the differences between the results from the two sets of coordinates are quite small for the lowest deflection, but become significant for the cases where $\delta_{FF} = \delta_{FA} = 10$ deg and 15 deg. Shearing results in a stretching of the trailing-edge flap, so that the effective flap chord is then incorrect and longer than that obtained when rotation is performed (when the flap chord is correct). Another significant feature when rotation is performed is the irregularity in the pressure distribution, which is particularly noticeable on the lower surface near the leading-edge flap hinge. This irregularity increases progressively with δ_{FF} , and is associated with the approach to a clash in the lower surface coordinates (see Section 3.1) as the flap deflection angle increases.

By removing from the surface geometry specification the two points nearest the forward hinge on the lower surface, sufficient smoothing is introduced effectively to eliminate the irregularity. This is shown by the results presented in Figure 3. The effects of introducing further smoothing, by removing two points from both upper and lower surfaces in the locality of both hinge positions (so that eight points are removed in all), are shown in Figure 4, where a comparison with the smoother of the two representations of Figure 3 is presented. The main effect of the further smoothing is the reduction in the heights of the peak suction in the upper surface pressure distribution. Lift and moment coefficients are little changed. The heights of the peaks in the pressure distribution are sensitive to the local surface curvature. The surface grid points computed by VGKSF corresponding to the two surface specifications of Figure 4 are shown in Figure 5. There is a clear difference in the local surface curvature, with removal of points from the surface specification producing the lower level of curvature (and the lower peaks). **For any flapped aerofoil of interest, if the actual detailed geometry near the hinge positions is known, then provided this geometry is smooth, it is feasible to vary the surface specifications (by removal of points) to try to obtain a good match between the surface grid points as generated by VGKSF and the actual geometry.** If a good

match is achieved, then the corresponding pressure distributions predicted by VGKSF, including the peaks near the hinge locations, should be reliable provided that other conditions, listed in Section 6, also hold.

4.2 Examples with Leading-edge Flap with Two Different Hinge Locations (on a Cambered Aerofoil)

In this Section calculated effects of deflecting a leading-edge flap of 10 per cent chord on the RAE2822 aerofoil (as specified by the file RAE2822.DAT, see Reference 2) are considered.

Two sets of flap hinge coordinates are considered corresponding to hinge locations on the lower surface, and on the upper surface. For each set $x_{HF}/c = 0.1$, and the two values of z_{HF}/c are -0.03869 and 0.03828 . A single flap deflection angle is considered, namely 10 deg, *i.e.* nose down. When the aerofoil and flap coordinates are generated by ADFLAPSH there is no effect of a change in the vertical position of the hinge. When the coordinates are generated by flap rotation using ADFLAP the vertical position does have an effect. With the hinge on the upper surface, nose-down flap deflection tends to produce a clash in the lower-surface specification, in the sense explained in Section 3.1.1, and with no smoothing applied to the coordinates, VGKSF generates irregular (and unrealistic) pressure distributions, as shown in Figure 6. With the hinge located on the lower surface the comparable pressure distribution is much more regular, as is shown also in Figure 6. In Figure 7a the corresponding pressure distributions obtained with two points removed from the surface specifications (for both upper and lower surface in each case) are shown. These distributions both appear quite regular, with the main difference between them being the more forward location of the upper-surface peak suction for the case with the hinge on the lower surface. This difference in location of the peak occurs because the region of highest surface curvature on the upper surface occurs rather more forward in the case when the hinge is on the lower surface, as shown in Figure 7b. Whether such a change in location would be obtained in practice would depend on how closely the surface geometries generated within VGKSF from the specified points corresponded to the actual flap/aerofoil geometries.

5. COMPARISONS OF VGK CALCULATIONS WITH OTHER RESULTS

5.1 Comparison with ESDU Method for Low Speed Flow

This comparison is for an aerofoil in low speed flow, having a plain control for which $c_{FA}/c = 0.35$. The aerofoil profile, which is symmetrical, is the same as the NACA 0010 profile (which has a thickness/chord ratio of 10 per cent), except that from 80 per cent of the chord to the trailing edge the profile comprises two straight lines. The trailing edge included angle, τ , is given by $\tan(\tau/2) = 0.097$. The Reynolds number based on aerofoil chord is 10^7 and boundary-layer transition is taken to occur at mid-chord.

By choosing this particular comparison, the data in the example of Reference 3 are applicable with only a minor change resulting from a small difference in trailing-edge angle. (A value of $\tan(\tau/2) = 0.12$ is considered in Reference 3.) Applying the method of Reference 3 for the rate of change of hinge-moment coefficient with control deflection yields $b_2 = -0.805 \text{ rad}^{-1}$. According to Reference 3, this value is applicable within the linear range of the hinge moment versus incidence curve, which corresponds generally to values of incidence and control deflection for which there is no flow separation around the aerofoil or flap. Within this range an accuracy of $\pm 0.05 \text{ rad}^{-1}$ can be expected in the estimation of b_2 . (Note that the symbol used in Reference 3 for this quantity is $(b_2)_0$, not b_2 . The suffix 0 is used there to denote two-dimensional flow. In this Item that suffix is omitted.)

Using the present method, with $M_\infty = 0.05$, the values for C_L , C_M , C_D and C_H given in Table 5.1 are found. Two different types of representation of the aerofoil with deflected flap are considered. These are generated by ADFLAP, in the first case with no specified surface points removed near the hinge, and, in the second case with two of these points removed from each upper and lower surface, see Section 3.1.1. These are referred to as 'unsmoothed' and 'smoothed' flap representations, respectively. The basic

symmetrical aerofoil profile is specified by 65 pairs of coordinates, with the points having a 'cosine' distribution over the chord similar to those in the file NAC0012.DAT described in Reference 2. The VGKSF files with the extension VIN, used as input for these runs, were obtained by first running VGKCON (see Reference 2 and Appendix A). All default parameters were set to their default values, except for the number of fine-mesh iterations, which was set to 400, rather than the default value of 200. All the VGKSF runs converged satisfactorily.

TABLE 5.1 Calculated results from VGKSF for deflected trailing-edge flap at low speed

Unsmoothed representations

α (deg)	δ_{FA} (deg)	C_L	C_M	C_D	C_H	b_2 (rad ⁻¹)
0	0	0	0	0.00418	0	
0	2.5	0.203	-0.0276	0.00422	-0.0360	-0.828
0	5	0.404	-0.0551	0.00426	-0.0723	
2.5	0	0.286	-0.0003	0.00458	-0.0218	
2.5	2.5	0.485	-0.0273	0.00476	-0.0565	-0.784
2.5	5	0.680	-0.0537	0.00571	-0.0902	
5	0	0.560	-0.0008	0.00644	-0.0393	
5	2.5	0.750	-0.0247	0.00747	-0.0710	-0.723
5	5	0.938	-0.0498	0.00840	-0.1024	

Smoothed representations

α (deg)	δ_{FA} (deg)	C_L	C_M	C_D	C_H	b_2 (rad ⁻¹)
0	0	0	0	0.00418	0	
0	2.5	0.202	-0.0276	0.00422	-0.0365	-0.840
0	5	0.404	-0.0552	0.00421	-0.0733	
2.5	0	0.286	-0.0003	0.00458	-0.0218	
2.5	2.5	0.485	-0.0274	0.00502	-0.0571	-0.794
2.5	5	0.679	-0.0537	0.00580	-0.0911	
5	0	0.560	-0.0008	0.00644	-0.0393	
5	2.5	0.750	-0.0248	0.00756	-0.0715	-0.737
5	5	0.938	-0.0499	0.00840	-0.1036	

It is seen from Table 5.1 that the calculated effects of flap deflection on C_L , C_M and C_H are almost linear with flap deflection at each incidence and also linear with incidence at each flap deflection. The values of b_2 presented in Table 5.1 are derived from the corresponding values of C_H at $\delta_{FA} = 0$ and 5 deg. It is also seen that there is little difference in the calculated coefficients attributable to the different flap representations, except for C_D , which is seen in one instance to be noticeably affected by the type of representation.

For none of the cases calculated is there any indication that the turbulent boundary-layer is close to separation (see Reference 1). However, for the flows with $\alpha = 5$ deg, the boundary-layer transition is calculated to occur close to the leading edge on the upper surface in the VGK calculations (rather than at