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VGK method for two-dimensional airfoil sections Part 3: estimation of a separation boundary in transonic flow



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VGK METHOD FOR TWO-DIMENSIONAL AEROFOIL SECTIONS
PART 3: ESTIMATION OF A SEPARATION BOUNDARY IN TRANSONIC FLOW

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VGK METHOD FOR TWO-DIMENSIONAL AEROFOIL SECTIONS PART 3: ESTIMATION OF A SEPARATION BOUNDARY IN TRANSONIC FLOW

1. INTRODUCTION

This Item is the third in a sequence dealing with the VGK aerofoil method. The Item describes the use of VGK to estimate a separation boundary for two-dimensional aerofoils in transonic flow in terms of lift coefficient and freestream Mach number. The basis of the Item is the method described in Transonic Data Memorandum No. 81020 (Reference 1), and the separation boundary corresponds to conditions on the upper surface of the aerofoil for which the shock strength and the adverse pressure gradient(s) are sufficiently severe for the trailing-edge pressure coefficient, relative to its trend with increasing lift coefficient or Mach number in attached flow, to have decreased by 0.05.

The full description of the underlying principles and limitations of the method, which is essentially based on 'calibrating' VGK results against experimental data, is given in Reference 1. The present describes only the detailed organisation of the computation involving VGK runs so as to obtain points on the separation boundary in a reliable and efficient way. For a description of the principles and typical results of the VGK method, reference should be made to Part 1 of the sequence of Items (ESDU 96028), whilst details of the various types of VGK runs, the naming convention and functions of various files and the use of the program VGKCON (the VGK 'control' program) are given in Part 2 (ESDU 96029).

The estimation of a single point on an aerofoil separation boundary requires a number of VGK runs to be performed. These runs constitute a 'sequence'. The first of such runs would normally relate to a combination of Mach number and incidence at which there were significant positive margins in terms of both the 'shock-upstream criterion' and the 'trailing-edge criterion'. These criteria are reproduced from Reference 1 as Figures 1a and 1b, where examples of positive margins are indicated. Successive VGK runs in the sequence are carried out at the same Mach number, with various values of incidence, until two successive VGK runs yield one or other of the margins sufficiently close to zero. (Two successive runs are required so as to ensure that VGK has adequately converged – see Section 4.) The values of Mach number and lift coefficient of the last VGK run in the sequence then constitute the single point on the separation boundary. The sequence of VGK runs is controlled by a Fortran program, SEPCON. This program produces a record of the flow conditions and criterion margins of the VGK runs, and at each stage in the sequence produces the files necessary for the next VGK run. The organisation of the commands to execute the VGK and SEPCON programs in a batch file is described in Section 5. Procedures for obtaining a number of points on an aerofoil separation boundary are also presented.

Estimated separation boundaries obtained using the present method are presented and compared with observed results in Section 6.

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2. NOTATION

Algebraic notation is printed in italics or has Greek symbols. Notation in VGK and SEPCON files is given in Roman type. Notation sequencing is based on the algebraic terms (except where none exists); some VGK and SEPCON notation therefore appears out of alphabetical order. All linear quantities made non-dimensional are based on aerofoil chord, c .

C_L	CL	aerofoil lift coefficient
C_{Lpot}	CLPOT	value of C_L found from jump in potential at trailing-edge (see Part 1)
C_{Lsep}	CLSEP	value of C_L on separation boundary
C_p	CP	pressure coefficient
c	C	aerofoil chord (see Sketch 2.1)
$\bar{H}$	HT	transformed boundary-layer velocity-profile shape parameter
j	NSG	number of radial lines in computing plane (see Part 1, Sketch 3.1)
k	K	number of circumferential grid lines in computing plane (see Part 1, Sketch 3.1)
M	EML	local Mach number (at edge of boundary-layer) based on isentropic flow relations
M_∞	EM	freestream Mach number
$M_{\infty sep}$	EMSEP	value of M_∞ on separation boundary
	NSF	number of iterations of inviscid-flow element using fine mesh
R	R	Reynolds number based on chord
	RES	maximum residual in inviscid-flow element
x		‘chordwise’ coordinate in physical plane (see Sketch 2.1)
z		‘normal’ coordinate in physical plane (see Sketch 2.1)
α	ALP	aerofoil incidence, <i>i.e.</i> angle between x -axis and freestream direction, positive nose-up (in degrees)
	AS1, AS2	specific values of α corresponding to DM1 and DM2, respectively
	AT1, AT2	specific values of α corresponding to DH1 and DH2, respectively
ΔM_{sh}	DM1, DM2	shock-upstream criterion margin values (see Figure 1a)
$\Delta \bar{H}_{\delta te}$	DH1, DH2	trailing-edge criterion margin values (see Figure 1b)

$\Delta\theta_L$	DD22	increment in non-dimensional momentum thickness at transition on lower surface
$\Delta\theta_L$	DD21	increment in non-dimensional momentum thickness at transition on upper surface
δ	DELTA	non-dimensional local boundary-layer thickness
θ	THETA	non-dimensional local boundary-layer momentum thickness
ω_f	GVISCF	relaxation factor associated with viscous effects using fine mesh
ξ	X	non-dimensional chordwise coordinate, $\xi = 0$ at leading-edge and $\xi = 1$ at trailing-edge
	XLE	value of x coordinate at leading edge
	XTE	value of x coordinate at trailing edge
ξ_{TL}	XTL	value of ξ corresponding to boundary-layer transition location on lower surface
ξ_{TU}	XTU	value of ξ corresponding to boundary-layer transition location on upper surface
ζ	Z	non-dimensional normal coordinate in physical plane

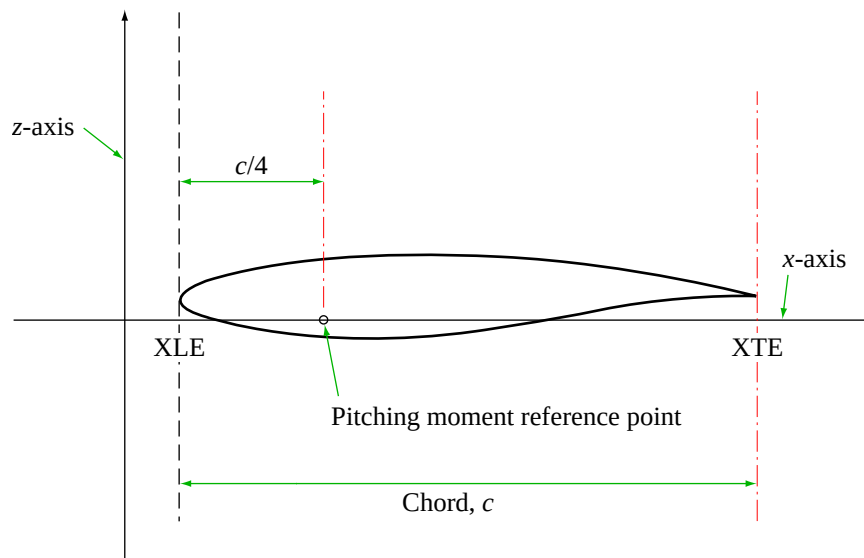
Subscripts

(File notation equivalents of subscripts appear in brackets)

sh	SH	denotes shock-upstream location
te	TE	denotes trailing-edge (refers to upper-surface boundary-layer)
P	P	a point on the aerofoil upper-surface at $\xi \approx 0.96$
Q	Q	a point on the aerofoil upper-surface at $\xi \approx 0.93$
δte		denotes point on the aerofoil upper-surface at $\xi = 1 - \delta_{te}$

2.1 VGK File Name Conventions

The file names used with VGK consist of a part provided by the user, comprised of 1 to 8 alphanumeric characters (no spaces are allowed), followed by a . (period) and a three letter extension denoting the type (or function) of the file. The extensions used are listed in Part 2 (Section 2.1.1) with their respective functions. In this Item “ABCD1234” is sometimes used to denote the user-provided part of the file name, although other usages, such as “AFS”, “AFC” and “S5234”, also occur. It is recommended that the user chooses file names that serve as a reminder of the work to which they refer and, more importantly, provide an identification of the VGK runs to which they refer. It is also recommended that any letters used in the file names be upper case.



Sketch 2.1 Aerofoil axes and notation

3. THE CRITERIA FOR PREDICTING SEPARATION

As described in Reference 1, two criteria are applied as follows to the turbulent boundary-layer of the upper-surface flow:

- (a) at the shock-upstream location (defined in Section 4.1.1 of Reference 1 in terms of a VGK calculation with $j = 160$, $k = 30$, which are the default values of these parameters, see Part 2),
- (b) one boundary-layer thickness ahead of the trailing-edge, (i.e. at $\xi = 1 - \delta_{te}$).

The criteria are:

- (a) For a given value of θ at the shock-upstream location, the value of M at the same location has the value given by Figure 1a, and
- (b) $\bar{H}_{\delta te} = 2.35 - 0.3 \log_{10} [R_c / (6 \times 10^6)]$, see Figure 1b.

Figures 1a and 1b also indicate the meaning of the M_{sh} and $\bar{H}_{\delta te}$ margins (denoted by ΔM_{sh} and $\Delta \bar{H}_{\delta te}$ respectively) as used in this Item. When one of the criteria is 'satisfied', the corresponding margin is zero. For a given aerofoil and flow condition* at a given value of $M_\infty (= M_{\infty sep})$, the value of C_{Lsep} is the lowest value of C_L for which either margin is zero as **determined from a converged VGK run**.

* Flow condition here includes the Reynolds number and the upper and lower surface transition locations.

4. METHOD OF OBTAINING A POINT ON SEPARATION BOUNDARY

The method of obtaining a pair of values $(M_{\infty sep}, C_{L sep})$ on the separation boundary as described in Reference 1 entails carrying out a number of VGK runs, with interrogation of the output of each run being undertaken prior to each successive run. The values of (M_{∞}, C_L) of the VGK runs define a 'calculation path' in the (M_{∞}, C_L) plane. It is recommended in Reference 1 that the calculation paths should be at constant M_{∞} where $C_{L sep}$ is expected to have its higher values and at constant incidence where $M_{\infty sep}$ is expected to be high. The interrogation of VGK output, and the step-by-step procedure described in Reference 1 which lead to the determination of a pair of values $(M_{\infty sep}, C_{L sep})$, have been replaced in this Item by an 'automatic' computational procedure and this is carried out by running the program SEPCON. Normally, calls to SEPCON would be made within a batch program or Shell procedure. In order for the parameters required for application of the two criteria to be processed readily by SEPCON, they are contained in a data file, ABCD1234.SEP (see Section 2.1), produced by a VGK run. In this sense, the version of VGK used in this Item, has been 'upgraded' from the version referred to in Reference 1. Also, because the procedure for arriving at a point on the separation boundary has been 'automated', there is no significant benefit in having two types of calculation path, so SEPCON generates only calculation paths with constant M_{∞} .

The program SEPCON (which is written in Fortran 77) carries out the following functions.

- (a) Reads and updates a record of M_{∞} , α , C_L , ΔM_{sh} and $\Delta \bar{H}_{\delta te}$ for each VGK run.
- (b) Determines whether a separation boundary criterion has been adequately satisfied.
- (c) Produces a .VIN file for any further VGK run that might be needed for a closer approach to the separation boundary.
- (d) Deletes a file (ACHLIM.DAT) if no further VGK run is needed, so enabling a batch program or Shell procedure containing a loop with SEPCON within it to be terminated.

Additional features of SEPCON are:

- (e) A batch program or Shell procedure containing a call to SEPCON within a loop will carry out no more than 21 calls to VGK, thereby avoiding the uncertainty resulting from a failure to satisfy the separation boundary criteria, and a consequent endless number of calls.
- (f) SEPCON saves the .IEH files of successive VGK runs, so enabling the convergence of these runs to be subsequently examined. These files are named A, B, . . . U, (see Section 5).
- (g) In order to reduce the computation times of VGK runs (which are the dominant computation times), the number of VGK fine-mesh iterations (see Part 2) is reduced by SEPCON from 100 to 50 after the fifth VGK run carried out for any one calculation path.
- (h) SEPCON generates a file (named SEPREC.DAT) which enables a graph showing the progression of the margins ΔM_{sh} and $\Delta \bar{H}_{\delta te}$ of successive VGK runs to be readily displayed.
- (i) SEPCON can deal with upper-surface flows having up to 5 shock waves. For VGK flows close to conditions of zero criteria margins, there would normally be only one shock in the upper-surface flow, but there may be two (or, very occasionally, more than two) such shocks at lower values of incidence.

- (j) SEPCON determines the two criteria margins by utilising relevant flow parameter values generated by VGK and written to the .SEP file. These include values of shock-upstream Mach number and θ , and values of $\bar{H}$ at the trailing-edge and at two further points on the upper surface denoted by P and Q, which are somewhat forward of the trailing-edge, at approximately $\xi = 0.96$ and $\xi = 0.93$. The precise values of ξ_P and ξ_Q (which depend on the particular aerofoil under investigation) are also written to the .SEP file.

Convergence to a point on the separation boundary is deemed to have been achieved when SEPCON produces two successive calls to VGK for nearly equal values of incidence with each giving a near-zero value for one of the separation margins (and a positive value for the other margin). The reason for requiring two successive VGK calls to satisfy these conditions is that convergence to a point on the separation boundary is carried out to some extent in parallel with convergence of the VGK flow iterations. A VGK run performed at an early stage of the calculation path is generally for an incidence that is significantly different from that of the immediately preceding run (from which it continues) and may well not fully converge in the 100 iterations allowed. A VGK run performed at a late stage of the calculation path is for an incidence value only slightly different from those of the few preceding runs, and so does effectively converge in the 50 (or 100) iterations performed in that run. When two successive VGK runs satisfy the stated conditions on incidence and separation margins then convergence of both the flow calculations and the approach to the separation boundary are assured.

If convergence to the point on the separation boundary has not been achieved within the maximum number of VGK calls (*i.e.* 21) allowed by SEPCON, then a second sequence, starting from the final conditions of the first one, should be run. Based on experience, this second sequence can be expected to achieve convergence to the point on the separation boundary with fewer than 10 VGK calls.

5. DETAILS OF PROCEDURE FOR OBTAINING POINT ON SEPARATION BOUNDARY

The procedure for obtaining a point on the separation boundary (defined by the method of Reference 1) for a particular aerofoil, at a particular combination of Reynolds number, R , and boundary-layer transition locations ξ_{TU} and ξ_{TL} , follows as Steps (a) to (f).

- (a) Select a value of M_∞ for which C_{Lsep} is required. This value of M_∞ is implicitly $M_{\infty sep}$.

Initially the value selected for $M_{\infty sep}$ should not be close to the extremes of the range of $M_{\infty sep}$ for which the method of separation estimation applies for the particular aerofoil and flow conditions of interest. The extremes are likely to be imposed (i) at the lower end of the Mach number range by the upper-surface shock location being within a few percent chord of the leading-edge and (ii) at the upper end of the Mach number range by the formation of a shock of significant strength on the aerofoil lower-surface.

For a 'new' aerofoil (*i.e.* one for which there is no prior knowledge of the transonic flow characteristics) it may not be clear initially how to avoid these limitations, and in such a case a preliminary series of VGK runs should be carried out so as to provide an indication of the range of Mach numbers which are clear of them.

- (b) Use VGKCON to produce input for a 'new' viscous VGK run with the following specification:
- (i) A suitable name, denoted in this Section as AFS (indicating aerofoil start).
 - (ii) The relevant aerofoil geometry data file.
 - (iii) A binary dump file to be produced.
 - (iv) The selected value of $M_{\infty sep}$ as the Mach number of the VGK run.