

DIRECT PREDICTION OF A SEPARATION BOUNDARY FOR AEROFOILS USING A VISCOUS-COUPLED CALCULATION METHOD

SUMMARY

The Data Item presents the principal features necessary in a viscous-coupled calculation method for it to be capable of predicting transonic flow around an aerofoil where there is some boundary layer separation. One widely used method (BVGK) which incorporates these features is a development of the VGK method (Reference 1). The BVGK method employs a semi-inverse coupling of the viscous and inviscid flow elements, and includes 'higher-order' terms in the formulation of the boundary layer and wake. It can deal with transonic flow with a subsonic free stream.

The Item gives an assessment of BVGK as a method of predicting separated transonic flows, by comparing results obtained using a BVGK code with data from wind tunnel experiments corrected to free air conditions. Attention is given to prediction of

- (a) aerofoil pressure distributions, especially indications of shock strength and location, and trailing-edge pressure,
- (b) separation boundary associated with trailing-edge pressure divergence, and
- (c) aerofoil drag coefficient for conditions near this separation boundary.

In the comparisons presented the separation boundary is well predicted (generally within 0.08 in C_L). This is true when the boundary is associated with either shock-induced separation or trailing-edge separation. The corresponding values of drag coefficient are fairly well predicted. However the code deals less satisfactorily with certain details and trends of the experimental pressure distributions. In particular the often observed gradual increase of trailing-edge pressure prior to its rapid fall (as separation becomes more extensive) is not predicted. It appears that BVGK tends to under-predict the extent (and effects) of shock-induced separation.

1. INTRODUCTION

Some of the calculation methods which couple viscous and inviscid flow elements are capable of predicting aerofoil flows with shock-induced boundary layer separation[†]. Such codes may therefore be used to predict separation boundaries directly, and also to predict aerofoil aerodynamic characteristics, such as drag and pitching moment, at conditions of lift coefficient and Mach number close to a separation boundary.

In this Item one such highly developed viscous-coupled method, known as BVGK, is considered with particular reference to the accuracy of the code's prediction of:

- (a) a separation boundary defined by trailing-edge pressure divergence[‡],
- (b) drag coefficient at conditions close to this boundary.

Also, since much useful information is provided from prediction of pressure distributions, these too are considered.

[†] Other codes, embodying approximate solutions to the Navier Stokes equations, are also capable of such predictions. These more complex codes, although potentially more accurate, have yet to be thoroughly assessed.

[‡] The degree of separation is defined (as in Reference 18) by $\Delta C_{p_{te}} = -0.05$, see Section 5.

Experimental aerofoil data, corrected to free air conditions, are used to assess the accuracy of BVGK. Flows examined involve one, or both, of the following:

- (a) separation commencing at or close to the foot of the shock,
- (b) separation near the trailing edge, well downstream of the shock.

Although only a small number of aerofoils is considered, the range of flows is relevant to many advanced supercritical aerofoils. Separation in shock-free flows is not considered.

In Section 3, following a brief outline of the general nature of viscous-coupled calculation schemes, a summary is given of the important features which should be included in order to achieve at least reasonably accurate results for transonic separated flows. This is followed by a description of the details of these features as they are incorporated in the BVGK code. Further relevant details of BVGK are presented in Section 4. In Section 5 results obtained using BVGK are compared with wind tunnel data corrected to free air conditions. These comparisons are evaluated and discussed in relation to the prediction of separated flows or where severe adverse pressure gradients occur. Recommendations are given in Section 6 regarding the use of BVGK (and comparable viscous-coupled methods) to predict the particular separation boundary considered and the associated drag.

2. NOTATION AND DEFINITIONS

2.1 Notation

All quantities of length made non-dimensional are based on the aerofoil chord, c .

C_D	(overall) drag coefficient, equal to $C_{D_V} + C_{D_W}$
C_{D_V}	viscous drag coefficient
C_{D_W}	wave drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
c	aerofoil chord
$\bar{c}_f$	equivalent skin-friction coefficient, equal to $2\tau_w/\rho_w u_{iw}^2$
H	shape parameter, equal to δ^*/θ
$\bar{H}$	transformed shape parameter, see Reference 3
H_1	mass flow shape parameter, equal to $(\bar{\delta} - \delta^*)/\theta$
IEIF, INPG INST, IHH1 ILRN, ICURVB	switches in BVGK program which activate corrections for various 'higher-order' effects, see Section 3

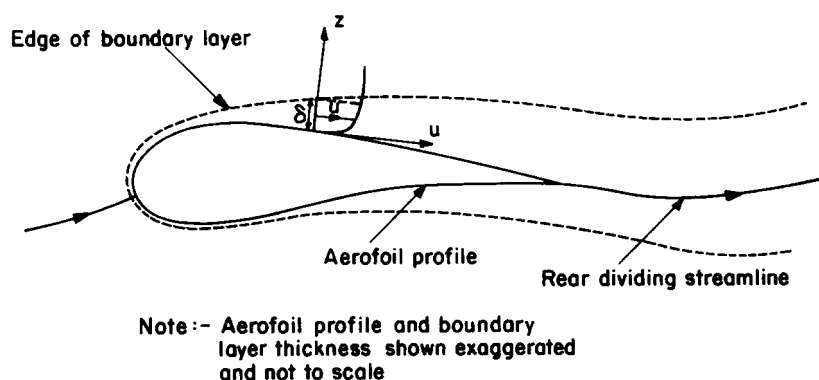
j	number defining computing mesh (Sketch 3.1)
k	number defining computing mesh (Sketch 3.1)
M_∞	free-stream Mach number
R	Reynolds number based on aerofoil chord, $\rho_\infty u_\infty c / \mu_\infty$
r	radial coordinate in plane $\sigma = re^{i\theta}$ (Sketch 3.1)
s	streamwise distance along aerofoil or rear dividing streamline; also coordinate orthogonal to z , increasing in sense of external flow velocity
t	aerofoil maximum thickness
u	velocity component in s coordinate direction, time mean velocity component where flow is turbulent
u_∞	free-stream speed
x	non-dimensional chordwise distance measured from leading edge of aerofoil
z	coordinate normal to aerofoil surface, zero on aerofoil surface
α	angle of incidence
δ	boundary-layer thickness
$\bar{\delta}$	equivalent boundary-layer thickness, see Reference 3
δ^*	boundary-layer displacement thickness
$\Delta C_{p_{te}}$	variation of $C_{p_{te}}$, see Section 2.2 (ix)
θ	boundary-layer momentum thickness; also polar coordinate in plane $\sigma = re^{i\theta}$ (Sketch 3.1)
λ	quasi-conservative parameter
μ	viscosity
ρ	density
σ	complex variable of interior circle plane (Sketch 3.1)
τ_w	wall shear stress
Suffixes	
i	denotes equivalent inviscid flow
s	denotes separation point
sep	denotes value where trailing-edge pressure divergence criterion is satisfied

sh	denotes shock location
te	denotes trailing edge – more specifically it denotes most rearward measuring location on upper surface (experiment), or nearest mesh point (on upper surface) to this location (BVGK)
w	denotes ‘wall’, <i>i.e.</i> aerofoil surface, conditions
1	denotes conditions just upstream of shock
∞	denotes free-stream conditions

2.2 Definitions

(i) Attached flow

A condition of the flow about an aerofoil corresponding to the *mean* velocity component, u , being positive everywhere close to (but not on) the aerofoil profile, see Sketch 2.1.



Sketch 2.1 Notation related to boundary layer

(ii) Separated flow

A condition of the flow about an aerofoil corresponding to u being negative at some points close to the aerofoil profile, see Sketch 2.2.

(iii) Separated flow region(s)

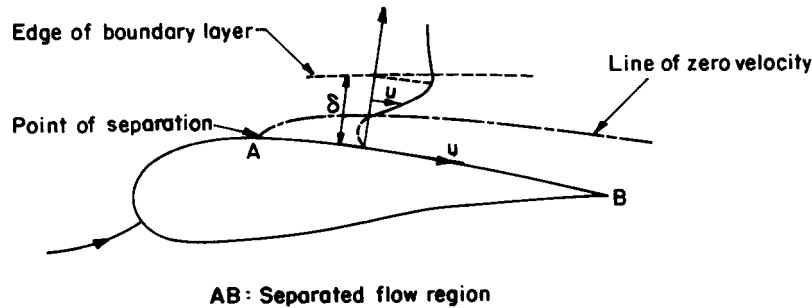
The portion(s) of the aerofoil profile, when separated flow occurs, corresponding to locations where u is negative at some points close to the aerofoil profile, see Sketch 2.2.

(iv) Line of zero velocity

Locus of points, when a separated flow occurs, (excluding points on the aerofoil profile) where u is zero, see Sketch 2.2.

(v) *Point of separation (or separation point)*

A point on the aerofoil profile approached from downstream along a line of zero velocity, see Sketch 2.2.

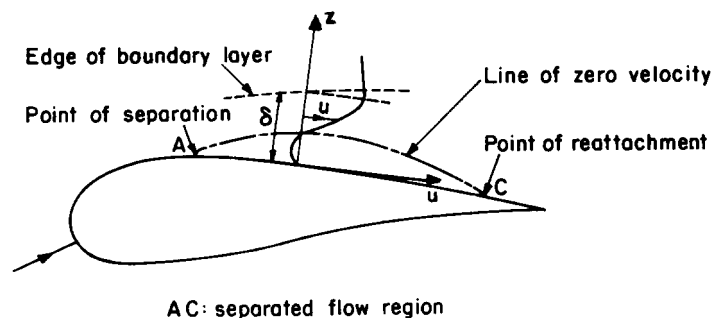


Note:— Aerofoil profile and boundary layer thickness shown exaggerated and not to scale

Sketch 2.2 Notation related to separation – no re-attachment

(vi) *Point of re-attachment (or re-attachment point)*

A point on the aerofoil profile approached from upstream along a line of zero velocity, see Sketch 2.3.



Note:— Aerofoil profile and boundary layer thickness shown exaggerated and not to scale

Sketch 2.3 Notation related to separation – with re-attachment

(vii) *Observed separated flow region(s)*

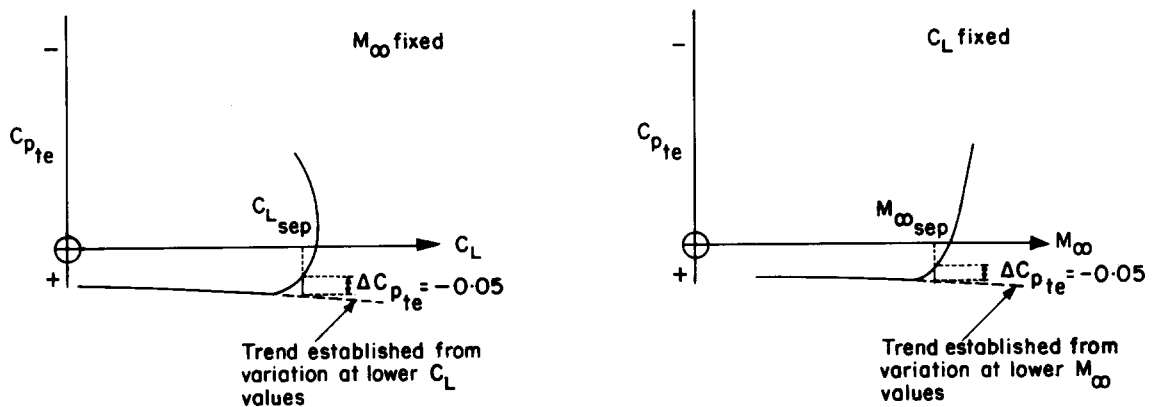
The extent(s), if any, of the aerofoil profile, corresponding to locations where either the measured wall shear stress is negative or zero, or some other experimental separated flow criterion is satisfied.

(viii) *Calculated separated flow region(s) (e.g. for a calculation scheme, such as BVGK, employing an integral boundary-layer method)*

The extent(s), if any, of the aerofoil profile, corresponding to locations where the calculated wall shear stress, τ_w , is negative or zero; or, what is equivalent, where $\bar{c}_f$ is calculated as negative or zero. Each extent is bounded upstream by a (calculated) point of separation, and is bounded downstream, where appropriate, by a (calculated) point of re-attachment.

(ix) *Trailing-edge pressure divergence criterion*

A criterion for expressing a degree of flow separation by means of either the variation of $C_{p_{te}}$ with C_L , at fixed M_∞ , or with M_∞ at fixed C_L . In particular the criterion is satisfied where one or other of the variations has shown a decrease in $C_{p_{te}}$ of 0.05 from a trend established at lower values of C_L or M_∞ , as appropriate (see Sketch 2.4). For brevity this criterion is referred to as the $\Delta C_{p_{te}} = -0.05$ criterion. The criterion may be applied either to observed or calculated data for an aerofoil. (There is some subjectivity in defining the trends but this has a very minor effect.)



Sketch 2.4 Trailing-edge pressure divergence separation criterion

(x) *Trailing-edge pressure divergence separation boundary*

The locus in the C_L, M_∞ plane of the points, denoted by $C_{L_{sep}}, M_{\infty_{sep}}$, at which the trailing-edge pressure divergence criterion is satisfied.

(xi) *BVGK*

BVGK denotes both the scheme of equations (and the solution methods) outlined in Section 4, and the various program codes by which these solution methods are implemented on a computer.

3. VISCOUS-COUPLED METHODS FOR TRANSONIC SEPARATED FLOWS

3.1 General Nature of Viscous-Coupled Methods

In many problems of aircraft aerodynamics the effects of viscosity and turbulence are confined to relatively thin shear layers in the vicinity of the 'wetted' surfaces and their wakes. Outside these 'viscous regions' the inviscid flow equations are applicable to a high level of accuracy. Viscous coupled methods (also known as viscous-inviscid interaction (VII) methods) take advantage of this fact and employ quite different calculation procedures for the external inviscid flow and the viscous shear layers. These two flow elements are linked, or 'coupled' (each element affecting the boundary conditions of the other), and an iterative procedure is used to produce a converged composite solution. This solution, comprising both the external inviscid flow[†] and boundary-layer/wake elements, then yields the required aerodynamic parameters, such as surface pressures, shear stresses, and overall forces and moments.

Viscous-coupled methods have reached an advanced state of development, particularly for two-dimensional flows. There is a variety of methods however, even for two-dimensional flows, and these methods can be broadly classified in terms of the equations and solution procedure governing each of their three main components, namely the inviscid flow, the shear layers and the coupling technique. Thus, the inviscid flow component may be determined either by solving the Euler equations or the equation for the velocity potential. In the latter case the adopted inviscid flow solution procedure for dealing with any shock waves may be either 'fully conservative', 'non-conservative', or 'partially conservative'. Similarly, the shear layers may be treated by a 'differential' or an 'integral' approach, with the latter being subject to numerous variations, the most important of which involve the incorporation of 'higher-order' terms. Finally, the coupling technique may be 'direct', 'inverse', 'semi inverse', or 'quasi-simultaneous', with further variations involving conditions relating to local boundary layer parameters. Added to these various categories the particular numerical techniques employed are also of relevance, especially for the inviscid flow element, where the type and refinement of the grid, the details of the shock capturing scheme, and the iterative solution procedure, are features which have a bearing on the solution obtained. Further details of these methods and examples of the influence of various features are given in References 2 and 3.

3.2 Important Features for Transonic Separated Flows

In the course of development of viscous-coupled methods, it has been found that methods which are capable of giving quite accurate results for transonic aerofoil flows at low and moderate lift coefficient may either fail or otherwise be quite inadequate for predicting flows with separation. Three main features are necessary to remedy this situation. These are as follows.

- (a) The inviscid flow solution must be capable of accurately predicting flows with strong embedded shock waves, *i.e.* where the Mach number just upstream of the shock may be as large as 1.4.
- (b) Since the shear layers at and near separation are not 'thin', carefully evaluated 'higher-order' terms need to be incorporated into the viscous flow element.
- (c) The coupling technique has to be one that can deal with both attached and separated boundary layer regions. One such technique is the 'semi-inverse' method; another is termed the 'quasi-simultaneous' coupling technique, see Reference 2.

[†] In most viscous-coupled methods the inviscid outer flow is extended (extrapolated) to the surface (and dividing stream surface) and is then termed the equivalent inviscid flow (EIF).

One viscous-coupled method which includes these features is known as BVGK and it is this particular method that is assessed in this Item. The BVGK method was devised at RAE, and is a development of an earlier viscous-coupled method known as VGK, see References 1 and 5. It employs Carter's scheme (Reference 4) for the semi-inverse coupling technique. It is capable of predicting both attached flows and flows with small extents of separation. Various versions of BVGK have now been generated but they all incorporate the three main features noted above, and the results obtained from them are largely indistinguishable. However, the later versions include various numerical refinements and are capable of yielding 'smoother' results for flows with significant separation.

The performance of a calculation method, in particular its accuracy of prediction, is dependent on the principal features embodied in the method and also, to a lesser degree, on numerous details of implementation. Provided a viscous-coupled method embodies the three main features listed above, its performance may be expected to be largely comparable with that of BVGK. However, details can be important and for this reason the specific forms of the three features as they are incorporated into BVGK are presented in Section 3.3.

3.3 Features of BVGK

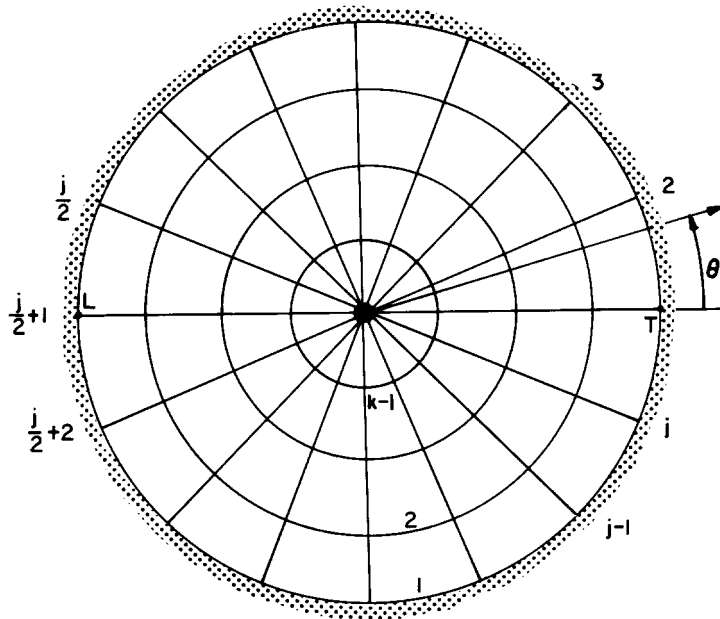
3.3.1 Inviscid flow

The inviscid flow element of the BVGK method is based on the solution of the velocity potential equation. This gives advantages of speed and simplicity as compared with methods based on solution of the Euler equations, but there is a disadvantage for flows with shock waves since flows calculated using the velocity potential do not satisfy the Rankine-Hugoniot shock relations, nor are the flow fields downstream of a shock accurately determined. Errors in the potential solution generally become more significant as shock wave strength increases. However, a modification to the solution procedure due to Lock and Collyer (Reference 6), which is incorporated into BVGK, results in the computed shock jumps being close to the correct values. This modification utilises the observation that numerical solutions of the potential equation cast in two different forms, namely the 'fully-conservative' (FC) form, and the 'non-conservative' (NC) form, yield differing shock jumps and shock locations, and that these differing solutions have errors of opposite sign. By introducing a 'mix' of these two basic solution schemes, a so-called 'partially-conservative' (PC) scheme results, and, properly applied, this yields flow fields which are nearly correct. The precise mix of the two basic schemes is governed by the 'quasi-conservative' parameter λ , where λ ranges between 0 and 1.0, with $\lambda = 1.0$ corresponding to the fully-conservative scheme. Lock and Collyer (Reference 7) present evidence supporting the use of the empirical rule:

$$\lambda = 1 - x_{sh}.$$

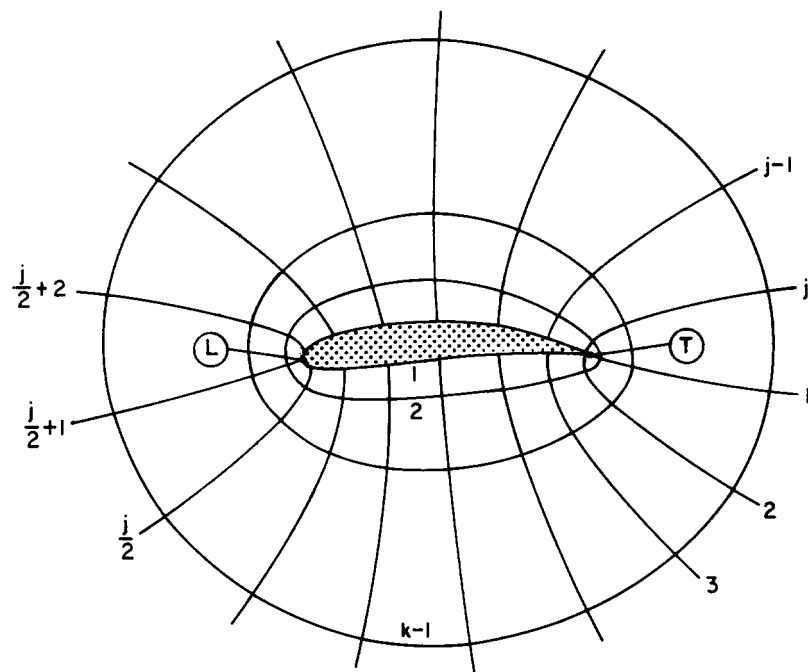
However, computed flows, with viscous effects included, are found to be fairly insensitive to changes in λ . The results presented in Section 5 generally correspond to $\lambda = 0.25$ and are appropriate to flows with shocks located aft of about mid-chord.

Solution of the inviscid flow equations in BVGK is performed on an 'O' type mesh, see Sketch 3.1, utilising 'successive line over-relaxation' (SLOR). Two mesh densities are normally employed, namely 80×15 and 160×30 , with the former being used in the initial stage of a calculation.



The transformed aerofoil (contour 1) is the unit circle and physical "infinity" (contour k) is at the origin

(a) REGULAR GRID IN COMPUTING PLANE ; MESH (j x k)



Contour k is at infinity

(b) IRREGULAR GRID IN PHYSICAL PLANE ; MESH (j x k)

Sketch 3.1 Representation of physical and computing plane meshes used in BVGK