



Viscous full-potential (VFP) method for three-dimensional wings and wing-body combinations

Part 2: Use of VFP and related programs

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PART 2: USE OF VFP AND RELATED PROGRAMS

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VISCOUS FULL-POTENTIAL (VFP) METHOD FOR THREE-DIMENSIONAL WINGS AND WING-BODY COMBINATIONS

PART 2: USE OF VFP AND RELATED PROGRAMS

1. INTRODUCTION

This Data Item describes a viscous-coupled version, VFP, of the Full-Potential method, FP which is associated with a series of Data Items^{1,2,3,4,5,6} dealing with three-dimensional wings and wing-body combinations. VFP is a CFD (computational fluid dynamics) method coded in FORTRAN for calculating the flow field about, and aerodynamic forces on, an isolated wing (denoted usually as a wing-alone) or a wing-body combination (denoted usually as a wing-body) in a subsonic freestream, including the effects of shock waves. VFP uses a relaxation process to solve finite-difference forms of the full nonlinear velocity-potential equation for the flow around the three-dimensional geometry. The VFP program was developed over a period of years at ARA, Bedford and RAE/DERA (now QinetiQ), Farnborough, and is made available by ESDU under the terms of an agreement with QinetiQ. Used originally on mainframe computers, VFP has provided valuable data in the design of a number of aircraft. With advances in computers, it has become possible to perform runs of VFP on a PC within a few minutes. One of the advantages of the VFP method is to provide a rapid process to produce valuable data to assess the aerodynamic qualities of wings as part of the design process. This version of the program to this process with a coupled semi-inverse swept tapered integral boundary-layer method devised by Ashill and Smith^{7,8}.

For the analysis of the aerodynamic characteristics of swept wings, it is often found convenient for high aspect-ratio cases to make the assumption that the flow is locally similar to that around an infinite yawed wing. The calculation of the boundary layer is thereby greatly simplified. A method of this type has been developed by Smith for calculating turbulent boundary-layers. This method, which is of the integral type, is coupled to the flow solver using a semi-inverse⁹ scheme which allows the calculation of flows with small amounts of separation. The method also includes other improvements to the modelling of the boundary layer which become more important as separation is approached. These improvements include the allowance for 'higher-order' effects in the correction for normal stress terms, a revised shape-parameter relationship which is more suitable for flows with separation and an improvement in the accuracy of the skin friction and the shape parameter of the velocity profile at low local Reynolds numbers.

Additional features include the provision of an increment in momentum thickness at the transition point to allow for trip drag and the capability to calculate viscous flows over forward-swept wings.

This Item, Part 2 in the Series dealing with VFP, is concerned primarily with the practical aspects of running VFP and its associated programs in order to obtain reliable results. The validation of VFP results with experiment and comparisons with other methods is given in Part 1 (Reference 10). VFP failures and flow error messages, and suggested remedies, are covered in Part 3 (Reference 11).

Section 2 presents the Notation and Conventions adopted and, for convenience, gives an index to the computer programs, parameters and filenames used.

A run of VFP is described in Section 3. For any run of VFP, in order to deal with a specific geometry at a particular Mach number and incidence, the following three input files are required:

GEOMFILE.GEO, which specifies the geometry of the wing-alone or wing-body which is created using the program FPCON, as described in Reference 2. The filename GEOMFILE.GEO may conveniently be changed by the user and its type must end with .GEO,

MAPFILE.MAP, which specifies the parameters that affect the computational grid and is also created using program FPCON (Reference 2). The filename MAPFILE.MAP may be changed by the user and its type must end with .MAP,

FLOWVIS.DAT, which specifies the flow conditions (namely the freestream Mach number, angle of incidence, Reynolds number and boundary-layer transition details), parameters that control the iterative calculations (including the form of finite-difference scheme used) and parameters that govern the extent of the output produced at each level of grid refinement. For wing-body calculations, the body may either be represented directly as a finite body, or indirectly as an infinite body together with disturbance Mach number increments to represent the effects of the nose and tail shaping albeit in an approximate manner. The disturbance Mach number increments over the wing due to the presence of a finite body at zero incidence may be determined by using ESDU 10014 (Reference 5). Again the filename may be changed by the user and its type must end with .DAT.

It is important to note that the three input files are fixed-format files which means that each parameter must occur at a specified location within the file. Any gaps between parameters must be filled only with spaces not tabs. Input files with the incorrect spacing or tabs will result in VFP either failing to produce a solution or producing an incorrect solution due to the input of an incorrect parameter value. Therefore, care needs to be taken in editing the input files when changing parameters such as Mach number, angle of incidence or number of iterations for example. Details of the fixed format and specification of the geometry .GEO and map .MAP files are given in ESDU 02014 (Reference 2) and the flow .DAT file specification is given in Section 4, here.

The VFP program is run by using the Windows batch file RUNVFP.BAT and a detailed description of this program is given in Section 5. The VFP wave-drag post-process program is discussed in Section 6. The various files output by the Windows batch file are discussed in Section 7.

1.1 Accuracy and Applicability of VFP

The range of results presented in Reference 10 show that VFP can produce accurate results for pressure distributions for cases without or with a weak shock. For conditions with stronger shocks, VFP can provide results with reasonable accuracy and capture the onset of shock-induced separation.

In terms of drag, VFP is capable of predicting the effects of alternative rear section design and sweep variation on viscous drag. Also, VFP can predict the variation of drag with Reynolds number and, when combined with the calculated effect of the transition trip on drag, provides a useful tool to adjust low Reynolds number experimental data to predict full-scale Reynolds number data. When combined with the prediction of lift-dependant and wave drags the method is capable of giving reasonable results for wing-drag polar and to capture drag rise with both lift and Mach number.

In terms of lift and pitching moment, VFP can produce results which match the trends due to the presence of shocks followed by the onset of flow separation.

For the prediction of the various boundary-layer parameters, VFP produces reasonably accurate results for swept wings without or with weak shocks. For cases with strong shocks and highly three dimensional flows

VFP tends to match the trend but not the values of some of the boundary-layer parameters. This is probably due to crossflow velocity profiles used in the swept-tapered method which were established for fairly small values of β .

VFP has been validated for a range of wings with aspect ratios from as low as 3 up to 20 and sweep variations from -40 degrees (forward sweep) to 40 degrees (aft sweep). Calculations have been performed up to a maximum Mach number of 0.90 and a minimum Reynolds number, based on mean chord, of 3 million. The method is capable of performing calculations at lower Reynolds number. However, for flows where transition is fixed by the presence of a laminar-flow separation bubble this feature is not modelled in the current method. Therefore it is suggested that cases with Reynolds numbers lower than 1 million should not be attempted. There is no limit on the maximum Reynolds number.

1.2 Program Access

The files required to run VFP and related programs on a PC are to be found in the folder (or directory) named VFPVG. Executable forms of the programs and Windows batch file to run VFP are provided.

To run VFP, carry out the following steps.

- Open a window for local disk C,

- Within the local disk C window, create a working directory,

- Copy all the files in the directory VFPVG to this working directory,

- An index of parameters, filenames and computer programs is given in Section 2.2 and detailed use of the programs is described in Section 3.

It is recommended that the PC used should have at least 128 MBytes of RAM, a hard disk drive with at least 500 MBytes of free space, and a processor speed of 1.6 GHz or more.

Although obtaining results using VFP is comparatively easy, care is required in interpreting them in relation to the task in hand. In general, this requires that all the Data Items concerned with the Full-Potential method be consulted in detail, namely References 1, 2, 10 and 11 in addition to this Data Item.

2. NOTATION

Parameters used in the input files for VFP are defined in ESDU 02014 (Reference 2) for the geometry and map files and Section 4 here for the flow file. In VFP, lengths are made dimensionless by division by c_0 , the centre-line chord. All quantities notionally of length (other than c_0) listed in this Section, such as R , s , c_c , x , y and z are thus non-dimensional, having been made so by division of the corresponding dimensional quantities by c_0 . Similarly, the reference wing areas S_g and S_1 have been made dimensionless by dividing the corresponding dimensional areas by c_0^2 . Note that the control section coordinates XSECT and ZSECT, see ESDU 02014 (Reference 2) are exceptions and are made dimensionless in a different way. Note also that the use of alternative wing reference areas are provided for, as are alternative definitions of aspect ratio and mean chord length. For details of the coordinate systems see ESDU 02014 (Reference 2).

C_D	overall drag coefficient, based on $S_1 c_0^2$
C_{DL}	local drag coefficient, based on local chord, cc_0
C_{DTV}	trailing-vortex drag coefficient
C_{DV}	viscous drag coefficient, based on $S_1 c_0^2$
C_{DVL}	local viscous drag coefficient, based on local chord, cc_0
C_F	local skin friction coefficient
C_L	overall lift coefficient, based on $S_1 c_0^2$
C_{LL}	local lift coefficient, based on local chord, cc_0
C_p	pressure coefficient
C_M	overall pitching moment coefficient about the moment reference point XCM (see Section 4.2), positive nose up, based on $S_1 c_0^2$ and $\bar{c}_1 c_0$
C_{ML}	local pitching moment coefficient, based on $c^2 c_0^2$
c	local chord
$\bar{c}$	mean geometric chord, $= S_g/2s$
c_c	chord of wing at crank (where applicable)
c_0	wing centre-line chord (dimensional), formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines to $y = 0$
$\bar{c}_1$	mean geometric chord, $= S_1/2s$
$\bar{H}$	transformed boundary-layer shape parameter (equivalent to “incompressible” H)
i	index denoting r coordinate of grid point, see Reference 2
j	index denoting η coordinate of grid point, see Reference 2

k	index denoting θ coordinate of grid point, see Reference 2
L, M, N	integer parameters related to numbers of mesh intervals; there are $L-2, M-2, N-2$ mesh intervals in (r, η, θ) directions, respectively
M_L	local Mach number
M_∞	freestream Mach number
q	local flow speed
q_{crit}	'critical' flow speed, <i>i.e.</i> local speed of sound
r, η, θ	cylindrical polar coordinates in computational space, see Reference 2
S_g	reference wing area, formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines to $y = 0$, see Reference 2
S_1	reference wing area, formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines with constant x coordinate, to $y = 0$, see Reference 2
s	wing semispan, measured from configuration centre line (<i>i.e.</i> not from wing root in case of wing-body)
U	local velocity ratio = q/V_∞
V_n	transpiration velocity
V_∞	freestream speed
x, y, z	Cartesian coordinates in physical space, see Reference 2
α	incidence angle, angle of inclination of x axis to freestream direction (positive nose up), deg
β	angle between limiting and external flow streamlines, deg
γ	circulation around wing section
Δ	increment
ΔC_{DTV}	excess trailing-vortex drag coefficient relative to ideal elliptic spanwise lift distribution
δ^*	boundary-layer displacement thickness for compressible flow
θ	boundary-layer momentum thickness for compressible flow also a cylindrical polar coordinate
ϕ	perturbation velocity potential
Λ	sweep angle (positive for sweepback), deg
η_s	spanwise position, = y/s

η_{sc}	value of η_s of crank section (where applicable)
ξ	dimensionless chordwise position, $\xi = 0$ at leading edge, $\xi = 1$ at trailing edge
ω	relaxation parameter (see Section 4.2)

Suffices

<i>c</i>	denotes crank
<i>i</i>	denotes inner panel (of cranked wing)
<i>inv</i>	denotes semi-inverse coupling
<i>le</i>	denotes leading edge
<i>nsh</i>	normal to shock
<i>sh</i>	shock
<i>te</i>	denotes trailing edge
<i>tip</i>	denotes (true) tip
<i>trip</i>	denotes transition trip
∞	denotes values far downstream, also denotes freestream value

2.1 Terminology

Some of the $\eta_s = \text{constant}$ grid lines on the wing surface of a wing alone or a wing-body lie in or very close to planes $y = \text{constant}$. They may thus be referred to as streamwise, or nearly streamwise, grid lines. For simplicity in this Item the $\eta_s = \text{constant}$ grid lines in the wing surface, and also the corresponding grid lines outboard of the tip, are usually described as 'streamwise'.

2.2 Index of Computer Programs, Parameters and Filenames

The following Index entries are parameters appearing in computer files unless otherwise indicated. For a parameter, the Section quoted is that where the definition appears. For programs and filenames the most significant Section(s) are given, in addition to a brief definition.

ABC	Section 4.2
ALAMD	Section 4.2
ALPD	Section 4.2
AMACH	Section 4.2
AREA	Section 4.2
CGCLEV	Section 4.2
cpdmach.dat	file output by vfptvkbbodyv8, Section 7.3 and Reference 5
cpnew.dat	file output by vfptvkbbodyv8, Section 7.3 and Reference 5
DELM	Section 4.2

delmach	file output by vfptvbodyv8, Section 7.3 and Reference 5
DELTHL	Section 4.2
DELTHU	Section 4.2
DIVERG	Section 4.2
EPS	Section 4.2
FLOWVIS.DAT	input file for VFP, Sections 1, 3 and 4.2
FPCON	program to produce wing geometry and map input files for VFP, Sections 3 and 5 and Reference 2
fuseout.dat	generic axisymmetric body file produced by vfpfusegenv2 program, Section 7.3 and Reference 5
GEO.DAT	wing geometry input file produced by FPCON, Sections 3 and 5 and Reference 2
GEOMFILE.GEO	input file for VFP, Sections 1 and 3
IFGC	Section 4.2
ILB	Section 4.2
ILPP(j)	Section 4.2
IOPT1(i)	Section 4.2
ITTY(j)	Section 4.2
IVINC	Section 4.2
JAVE	Section 4.2
JAVE1	Section 4.2
JAVE2	Section 4.2
JGAM(i)	Section 4.2
JGAM(1)	Section 4.2
KAVE	Section 4.2
KAVE1	Section 4.2
KAVE2	Section 4.2
MAPFILE.MAP	input file for VFP, Sections 1 and 3
MJ	Section 4.2
NDELM	Section 4.2
NITS	Section 4.2
NK	Section 4.2
NL	Section 4.2
NLPP	Section 4.2
NOUTS	Section 4.2
NTEST	Section 4.2
NTOL	Section 4.2
NTTY	Section 4.2
NU	Section 4.2
NXTCRD	Section 4.2
RC	Section 4.2
RNDR	Section 4.2
ROVR	Section 4.2
TITLE	Section 4.2
TOLCD	Section 4.2
TOLCL	Section 4.2
vdrag.res	file output by the vortex drag routine in VFP, Section 7.1
VFP	program to implement viscous full-potential method, Section 1
vfpcplot	Microsoft Office Excel plotting spreadsheet for pressure coefficient distribution, Section 7.1
vfpfusegenv2	generic axisymmetric body program, Section 7.3

vfptvkbodyv8	axisymmetric body disturbance Mach number program, Section 7.3
vfpviscous	Microsoft Office Excel plotting spreadsheet for viscous parameters, Section 7.1
vort.res	file output by the vortex drag routine in VFP, Section 7.1
wave87003	wave drag program, Section 6
wingfuse.dat	file output by vfptvkbodyv8, Section 7.3 and Reference 5
XCINVL	Section 4.2
XCINVU	Section 4.2
XCM	Section 4.2
XCTRIPL	Section 4.2
XCTRIPU	Section 4.2
YDELM	Section 4.2
YFIXL	Section 4.2
YFIXU	Section 4.2

3. DESCRIPTION OF VFP RUN

3.1 Definition

A VFP run is defined as a calculation using the VFP code for a specified three-dimensional geometry, with a particular selection of the parameters controlling the grid generation, and a particular selection of the parameters controlling the iterative process of calculating the flow field(s).

The iterative flow-field calculation comprises a sequence of one or more steps, each step corresponding to a number of iterations on a grid of a particular refinement level. The finest grid (level 1) corresponds to the grid as produced by the grid generator. The medium grid (level 2) has half the level 1 numbers of grid intervals in each of the three coordinates, whilst the coarsest grid (level 3) has the same grid intervals as in level 2 in two of the coordinates, but half the level 2 number of intervals in the third coordinate, *i.e.* around the 'streamwise' sections. The general features of grid generation are described in ESDU 02013 (Reference 1).

3.2 Spanwise Arrangement of Streamwise Grid Lines

The generation of the .GEO and .MAP input files are explained in ESDU 02014 (Reference 2) using the FPCON program.

Prior to running VFP it is important that the fine-grid spanwise distribution of (nearly) streamwise grid lines is checked to make sure there is an even number of streamwise grids between the root and tip. This is essential because, for the viscous calculation, the first spanwise location (root) and last grid location (close to the wing tip) are inviscid – resulting in an even number of viscous locations and preventing a failure of the viscous grid locations at the coarse and medium grid levels. Details on checking and refining the computational grid are explained in ESDU 02014.

3.3 Flow Calculation

Once the grid calculation is complete, the flow calculation which follows has three levels of grid refinement: from coarse (level 3), to medium (level 2), to fine grid (level 1). The first viscous calculation of the initial run is always carried out after 50 inviscid iterations at coarse grid level. This is then followed by a viscous calculation after every 10 inviscid iterations for the remaining flow calculations. It is recommended to start the initial calculation at a low angle of incidence or Mach number and to save the flow and viscous dump files once a suitable level of convergence is reached at fine grid. The level of convergence is monitored by

recording the values of integrated lift coefficient C_L and drag coefficient C_D for every 500 fine grid iterations. There is an option to apply a convergence test based on C_L and/or C_D within the FLOWVIS.DAT file that avoids the necessity of examining the VFP output to see whether or not a reasonable convergence level has been achieved. The advantage of not using the convergence option within the FLOWVIS.DAT file is that it gives the user the flexibility to restart the calculation from the previous dump files and adjust the relevant flow parameters if the solution fails. Once the initial flow calculation is complete the flow and viscous dump files are used as a starting condition for the next increase in angle of incidence or Mach number and the flow calculation is continued until a suitable level of convergence is achieved. This process is repeated with further increases in angle of incidence or Mach number until the solution starts to diverge due to the onset of flow separation. An example of a continuation calculation is given in ESDU 13013, Reference 10.

After completion of each set number of fine grid iterations of flow calculation is completed, various sets of output are produced. Results are given for C_L , C_D , C_{DV} , C_{DTV} and C_M along with C_{LL} , C_{DL} , C_{DVL} and C_{ML} at each streamwise grid along the exposed wing. Also output are the C_p values around each streamwise section. Boundary-layer parameters θ/c , δ^*/c , $\bar{H}$, and c_f are also output around each streamwise section excluding the first (wing root) and last (close to wing tip) station on the exposed wing.

VFP produces detailed output results for the region of the exposed wing only. No detailed pressures on the body are output, and the overall lift and drag coefficients are evaluated by assuming that these are the same as if the local values of chord, lift coefficient and drag coefficient were each constant between the centreline and the most inboard grid section on the exposed wing. In addition, an alternative method to estimate overall lift, with improved estimate of body-lift contribution, is calculated using the relationship given in ESDU 02015, Reference 3. For the viscous drag the values of local viscous drag at the root and the station nearest to the wing tip are each based on a linear extrapolation of the local viscous drag levels of the two nearest streamwise grid stations.

4. SPECIFICATION OF THE VFP INPUT FILE FLOWVIS.DAT

The flow field calculations carried out by VFP on a particular grid are determined by the parameters provided by file FLOWVIS.DAT. The majority of parameters are the same as specified in ESDU 02014, Reference 2 apart from the additional parameters required for the viscous calculation. For completeness the input details given in Reference 2 are repeated in this Section. As previously stated, the flow input file is a fixed format file with each parameter at a specified location within the file. Any gaps between parameters must be filled only with spaces, not tabs. Appendix A, Section A2 gives two examples of typical FLOWVIS.DAT files.

4.1 Lines of Data Appearing in FLOWVIS.DAT

Sixteen different types of data lines may be used in FLOWVIS.DAT[†]. The line type numbers are 0, 0A, 0B, 1A, 1B, 2, 3, 4, 5, 6, 7C, 8C, 9C, 10C, 11C and 12. A FLOWFILE.DAT file always commences with lines of type 0 and 0A, and terminates with a line of type 12. The remaining lines in the file are in blocks, each such block corresponding to a flow calculation step. In each block, lines of type 1A, 1B must appear, and lines of type 2 to 6 may appear. Whether or not lines of type 2 to 6 appear in any block is determined by the currently held value of NXTCRD. This is the first parameter in lines of type 1A, 2, 3, 4, 5, 6, and the only parameter in a line of type 12. Unless NXTCRD is set to zero (as NXTCRD is by a line of type 12) the value of NXTCRD specifies the type of the line to be input next. (When NXTCRD is set to 1, the next two lines to be read are of type 1A and 1B.) If a line of type 2, 3, 4 or 5 is omitted, then the parameters that they would have specified are set to particular values, called program default values, as given in

[†] The numbering system used for the data line reflects the program development, and the fact that the original input was by means of punched cards.

Section 4.2. If a line of type 6 is omitted then no convergence criterion based on C_L and/or C_D is applied. Lines 7C to 11C are additional to those given in ESDU 02014, Reference 2, and contain input data required by the viscous routine.

The following definitions specify the data provided by the sixteen line types, and the formats used. Note that the format specifications are given in Fortran nomenclature for input.

Line type 0 (Format of line type 0: 10A8)	TITLE
Line type 0A (Format of line type 0A: I5)	NDELM
Comment	Line type 0B follows, unless NDELM = 0, in which case line type 1A follows.
Line type 0B (Format of line type 0B: 2F10.0)	YDELM, DELM
Comment	Further lines of type 0B follow, if necessary, until there are NDELM such lines, in which case line type 1A follows.
Line type 1A (Format of line type 1A: I2, 3X, 20I1, I5, 3F10.0)	NXTCRD, IOPT1(i), $i = 1$ to 20, NITS, AMACH, ALPD, XCM
Line type 1B (Format of line type 1B: 2X, 4F5.0, 6I5)	ROVR, RNDR, EPS, ALAMD, JAVE, KAVE, JAVE1, KAVE1, JAVE2,
Line type 2 Format of line type 2: I2, 3X, 55I1	NXTCRD, ITTY(j), $j = 1$ to 55
Line type 3 (Format of line type 3: I2, 3X, 55I1)	NXTCRD, ILPP(j), $j = 1$ to 55
Line type 4 (Format of line type 4: I2, 3X, 7I5)	NXTCRD, NTTY, NLPP, JGAM(i), $i = 1$ to 5
Line type 5 (Format of line type 5: I2, 3X, 3F10.0)	NXTCRD, CGCLEV, DIVERG, AREA
Line type 6 (Format of line type 6: I2, 3X, 4I5, 2F10.0)	NXTCRD, IFGC, NTOL, NTEST, NOUTS, TOLCL, TOLCD
Comment	Line types 7C to 10C follows if the viscous option is IOPT1(11) = 1 or 2.
Line type 7C (Format of line type 7C: I5)	IVINC
Line type 8C (Format of line type 8C: F10.6, I5, F10.6, 2I5)	RC, MJ, ABC, NK, ILB