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Full-potential (FP) method for three-dimensional wings and wing-body combinations – inviscid flow Part 1: Principles and results

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FULL-POTENTIAL (FP) METHOD FOR THREE-DIMENSIONAL WINGS AND WING-BODY COMBINATIONS - INVISCID FLOW PART 1: PRINCIPLES AND RESULTS

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FULL-POTENTIAL (FP) METHOD FOR THREE-DIMENSIONAL WINGS AND WING-BODY COMBINATIONS – INVISCID FLOW

PART 1: PRINCIPLES AND RESULTS

1. INTRODUCTION

FP is a CFD (computational fluid dynamics) method coded in Fortran for calculating the flow field and aerodynamic forces of 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. FP 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 FP program was developed over a period of years at ARA, Bedford and RAE (now QinetiQ), Farnborough, and is made available by ESDU International plc under the terms of an agreement with QinetiQ. Used originally on mainframe computers, FP has provided valuable data in the design of a number of aircraft. With advances in computers, it has become possible to perform runs of FP on a PC within a few minutes.

The FP code results presented in this Item have all been produced from runs on a PC. The version described takes no account of the boundary layer or viscous wake, but it is intended that an enhanced version (denoted VFP) that does take account of viscous effects, albeit in a simplified manner, will be issued subsequently. The guide for running FP comprises Part 2, and is issued as a separate Data Item (Reference 1). This Item provides an account of the principles of FP, a number of results, and comparisons with other methods and with experiment.

In common with other CFD codes, FP comprises two distinct elements, the grid generator and the flow solver. The main features of these elements are described in Section 3.

The performance of FP is considered in Sections 4 and 5. In Section 4, some basic results for subcritical flows are presented first, followed by results for flows with shock waves. Comparisons with experimental data are given in Section 5, and these indicate typical differences between inviscid and real flows.

In Section 6 remarks are made concerning the accuracy and applicability of FP.

1.1 PROGRAM ACCESS

The files required to run FP and related programs on a PC are to be found in the folder (or directory) named FPV20. Executable forms of the programs are included, so no Fortran compiler is required. (Source code is available for some programs, such as FPCON and CONTOUR, but not for FP and MAPONLY.)

To run FP, carry out the following steps.

- (1) Open a 'C:\ Command Prompt' window or 'box'. (In some Windows versions the C:\ Command Prompt is an Accessory, in others it is a Program.)
- (2) Within the C:\ Command Prompt window, create a working directory.
- (3) Copy all the files in the directory FPV20 to this working directory.

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- (4) Read the contents of the file README20.DAT (which is one of the files copied), using an editor or other suitable application.
- (5) Proceed according to the directions given in that file.

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 1.5 GHz or more.

Although obtaining results using FP 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. Where overall lift and drag are of interest, it is particularly important that Parts 3 and 4 (References 11 and 12) be consulted.

2. NOTATION AND COORDINATE SYSTEMS

In the Notation used for FP, lengths are made dimensionless by division by c_0 , the centre-line chord, see below. All quantities notionally of length (other than c_0) listed in this Section, such as c , c_c , x , y and z are thus non-dimensional, having been made so by division of the corresponding length quantities by c_0 . Similarly, the reference wing areas S_g and S_1 have been made dimensionless by dividing the corresponding actual areas by c_0^2 . Note that alternative wing reference areas are defined, as are alternative aspect ratios and mean chord lengths. Further notation, utilised in FP files, but not used specifically in this Item, is defined in Part 2.

A_g	(gross) wing aspect ratio, $= 4s^2/S_g$
A_1	wing aspect ratio, $= 4s^2/S_1$
c	local chord
$\bar{c}$	mean geometric chord, $\bar{c} = S_g / 2s$
$\bar{c}_1$	mean geometric chord, $\bar{c}_1 = S_1 / 2s$
c_0	centre-line chord, formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines to $y = 0$
c_c	chord of wing at crank (where applicable)
c_t	chord of wing at tip
C_D	overall drag coefficient, based on S_1
C_{DL}	local drag coefficient, based on local chord
C_{DV}	vortex drag coefficient, based on S_1
C_{DW}	wave drag coefficient, based on S_1
C_L	overall lift coefficient, based on S_1

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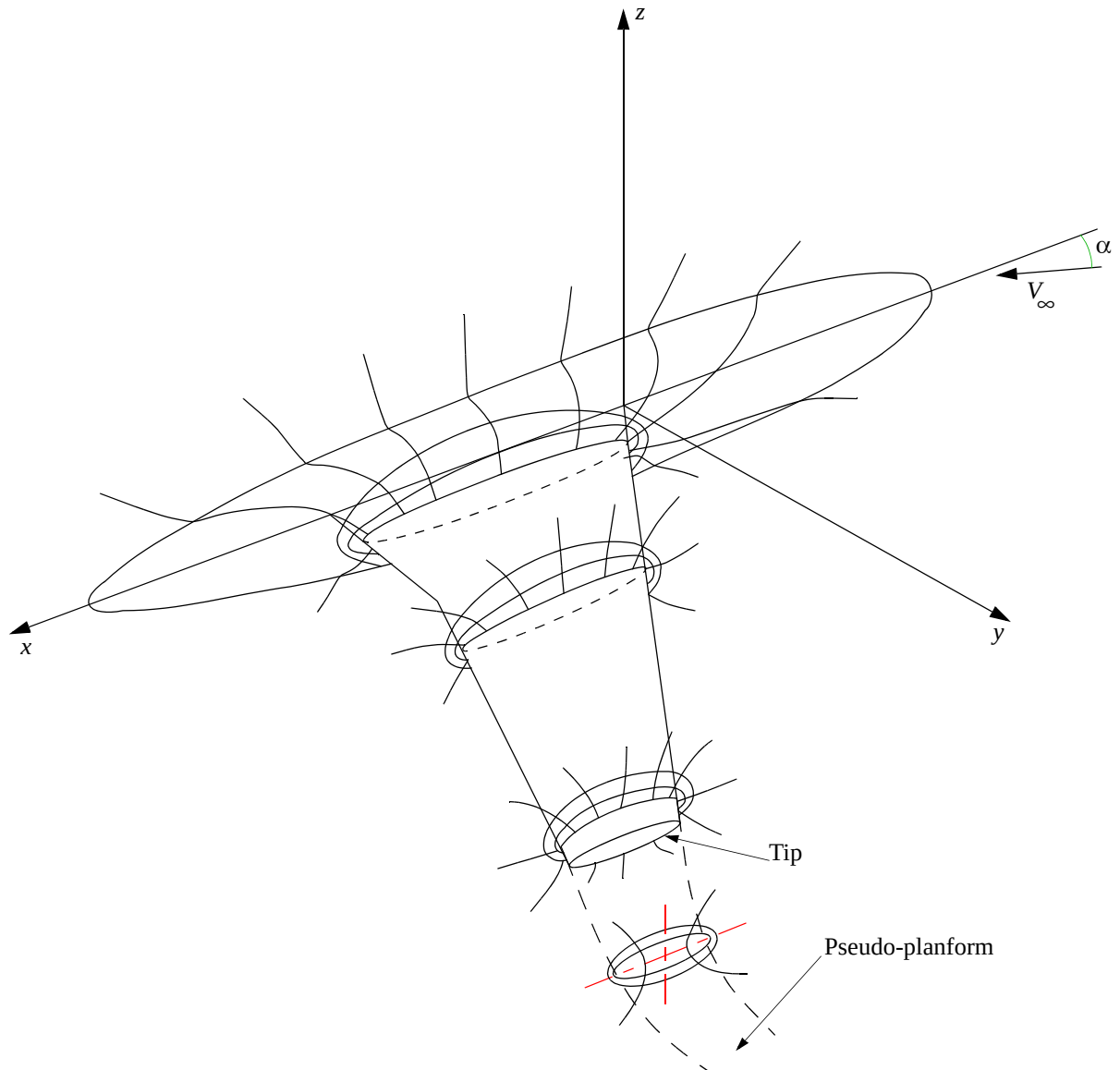
C_{LL}	local lift coefficient, based on local chord
C_p	pressure coefficient
i	index denoting r coordinate of grid point (see Sketch 2.3)
j	index denoting η coordinate of grid point (see Sketch 2.3)
k	index denoting θ coordinate of grid point (see Sketch 2.3)
L, M, N	integer parameters related to numbers of mesh intervals; there are $L-2$, $M-2$, $N-2$ mesh intervals in (r, η, θ) directions, respectively
M_∞	freestream Mach number
M_{Lnsh}	Mach number corresponding to velocity component normal to shock wave (just upstream of shock wave)
q	local flow speed
q_{crit}	'critical' flow speed, i.e. local speed of sound
r, η, θ	cylindrical polar coordinates in computational space (see Sketch 2.3)
R	body radius (may vary with x)
s	wing semispan, measured from configuration centre line (i.e. not from wing root in case of wing-body)
S_g	(gross) reference wing area, formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines to $y = 0$ (see Sketch 2.4)
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 Sketch 2.4)
V_∞	freestream speed
x, y, z	Cartesian coordinates in physical space (see Sketch 2.1)
x', y', z'	Cartesian coordinates in intermediate space (see Sketch 2.2)
y_G	average spanwise coordinate in physical space of grid line on wing surface having constant η
α	incidence angle, angle of inclination of x axis to freestream direction (positive nose up), deg
ϕ	perturbation velocity-potential
γ	circulation around wing section
Λ	sweep angle (positive for sweepback), deg
λ	(gross) taper ratio, $= c_t$

λ_i	(gross) taper ratio of inboard panel of cranked wing (where applicable), = c_c
η_s	dimensionless spanwise position, = y/s
η_{sc}	value of η_s of crank section (where applicable)
ξ	dimensionless chordwise position, $\xi = (x - x_l)/c$ ($\xi = 0$ at $\xi = 0$ at leading edge, $\xi = 1$ at trailing edge)
<i>Suffices</i>	
<i>const</i>	denotes constant value (in relation to R)
<i>crank</i>	denotes crank
<i>i</i>	denotes inner panel (of cranked wing)
<i>le</i>	denotes leading edge
<i>o</i>	denotes outer panel (of cranked wing)
<i>q</i>	denotes quarter chord location
<i>te</i>	denotes trailing edge
<i>tip</i>	denotes (true) tip

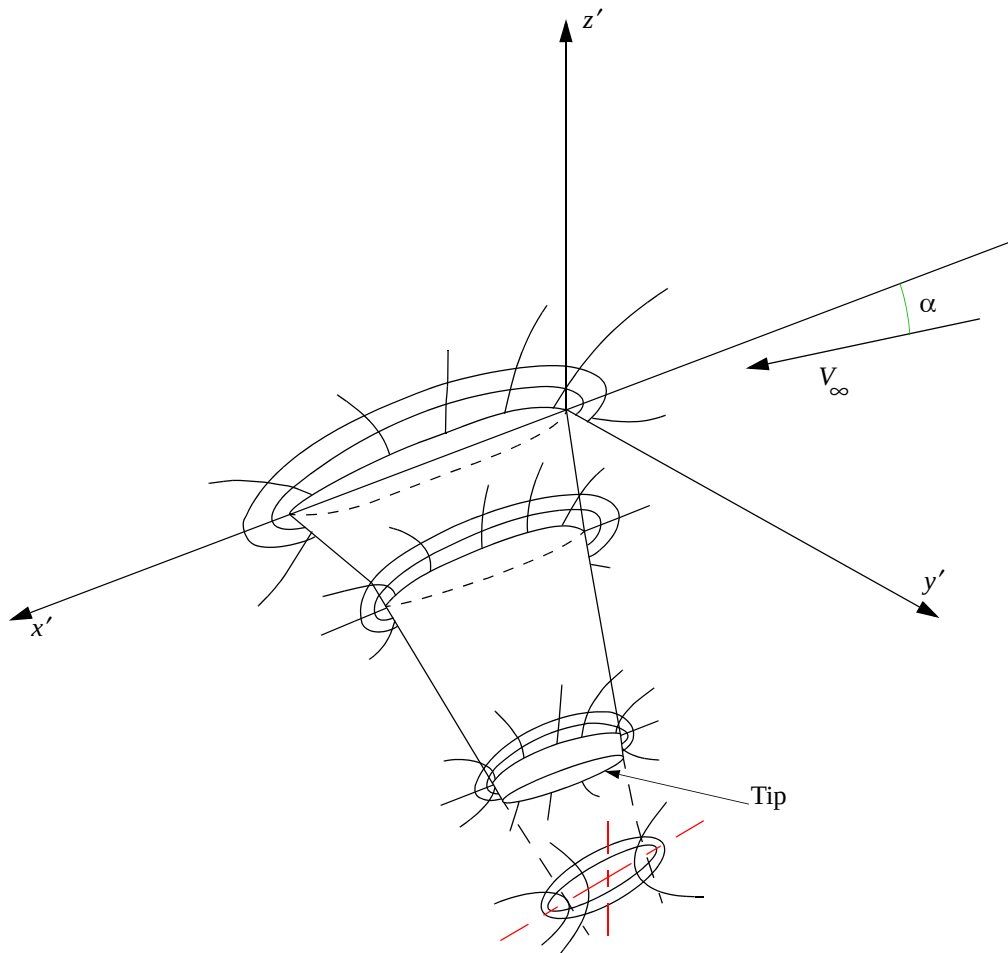
2.1 Terminology

Some of the $\eta = \text{constant}$ 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 $\eta = \text{constant}$ grid lines in the wing surface, and also the corresponding grid lines outboard of the tip, are usually described as 'streamwise'.

2.2 Coordinate Systems

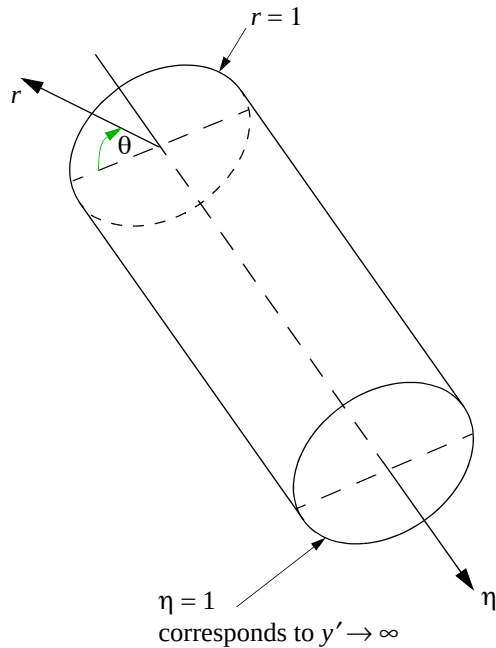


Sketch 2.1 Coordinate system in physical space



Sketch 2.2 Coordinate system in intermediate space

Wing section in intermediate space mapped
to circles $r = 1$, $\eta = \text{constant}$ in computational space



$L-2$ equal grid intervals in r direction
 $M-2$ equal grid intervals in η direction
 $N-2$ equal grid intervals in θ direction

$i = 2$ corresponds to $r = 0$

$i = L$ corresponds to $r = 1$

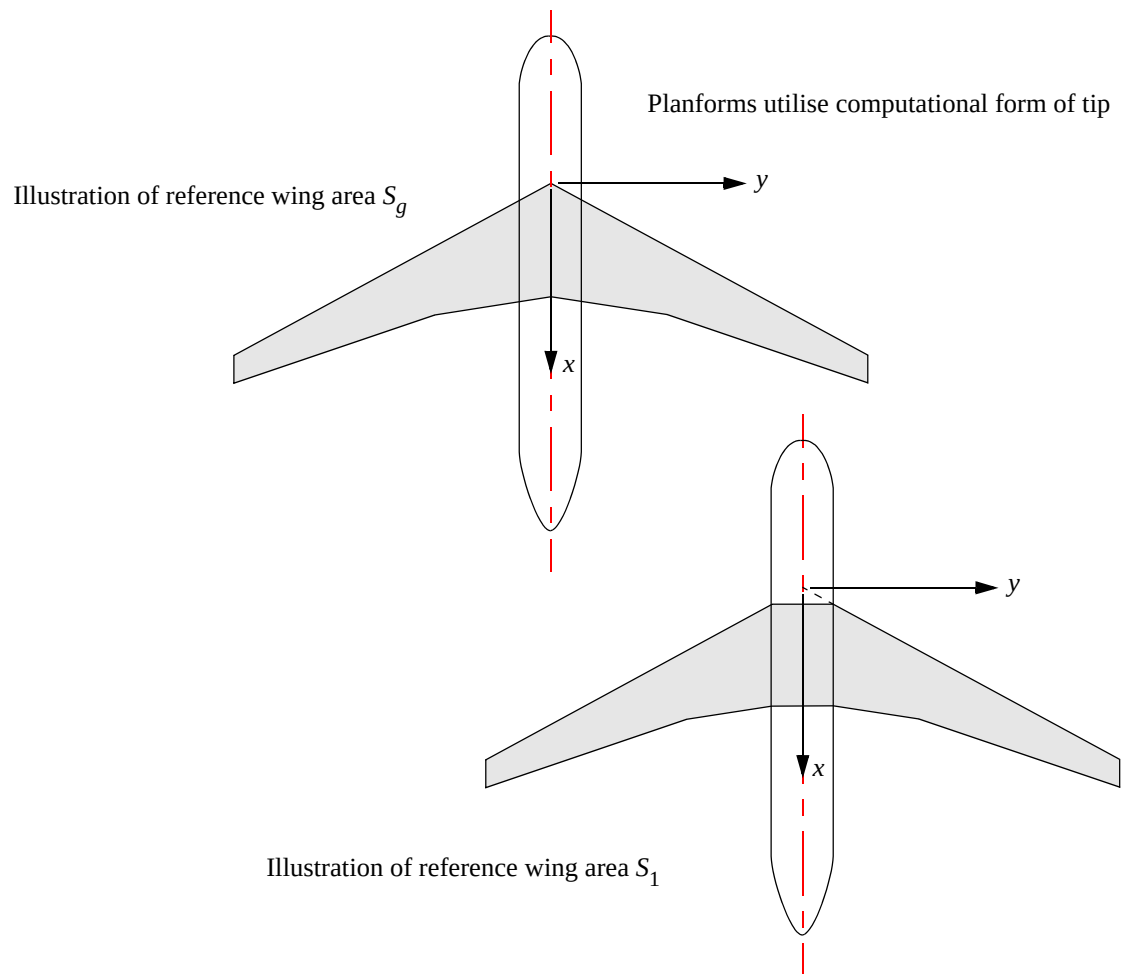
$j = 3$ corresponds to $\eta = 0$

$j = M + 1$ corresponds to $\eta = 1$

$k = 2$ corresponds to $\theta = 0$ (trailing edge on lower wing surface)

$k = N$ corresponds to $\theta = 2\pi$ (trailing edge on upper wing surface)

Sketch 2.3 Coordinate system in computational space



Sketch 2.4 Illustration of reference wing areas S_g and S_1

3. PRINCIPLES OF FP METHOD

3.1 Grid Generator

The grid generator of FP sets up a computing grid in a transform space that consists of the interior of a unit length circular cylinder of unit radius, and computes all the transform derivatives and the coefficients of the flow equation that depend only on these derivatives. These transform derivatives and coefficients are utilised by the flow solver. The coordinates in the transformed space are (r, η, θ) , where η is the coordinate along the length of the circular cylinder, and r and θ are respectively the radial and azimuthal coordinates in the cylinder, see Sketch 2.3.

Configurations that may be dealt with are an isolated wing, also referred to as a 'wing-alone', and a wing-body combination, where the body is axially symmetric. The configurations are assumed to be symmetric about the plane $y = 0$. Wing planforms may have straight or curved leading- and trailing-edges, and these edges may contain slope discontinuities (cranks). The body may be infinite or finite in length, but the grids employed are not sufficiently dense to enable finite body length effects to be treated accurately. The wing geometry is specified by a number of control sections in planes $y = \text{constant}$ (up to 38 may be employed), together with corresponding twist (rotation) angles and centres of twist. The twisted sections are established and the wing geometry is interpolated between these. The form of interpolation may be selected by the user (see Part 2).

A number of restrictions apply to the geometrical configurations that may be dealt with successfully by FP. For example, the (maximum) radius of any body present must be neither too small nor too large in relation to c_0 . Also the wing taper ratio should not be too small, and any forward wing sweep should not be too large. These restrictions have not been established precisely, but the examples given in Part 2 provide a fair indication of the geometrical configurations that may be dealt with successfully by FP.

The transformation that maps the physical space around a wing-body is in two parts. The first part maps the half-body, and the part of the plane $y = 0$ outside the body, onto the plane $y' = 0$, and produces a wing-alone in an 'intermediate space'. The root and tip in the intermediate space correspond respectively to the wing-body junction and the tip in physical space. The second part of the transformation (which is the sole transformation applied if the geometry of interest is a wing-alone) maps wing sections in the intermediate space into unit circles by conformal transformations, and applies an analytic transformation spanwise. The analytic transformation may be selected so as to pack wing sections corresponding to grid lines relatively closely near the root and tip (and near the crank also, if there is one) and to bring (spanwise) infinity to a finite plane. The space outside each wing section is mapped to the inside of a unit circle, in the same way as in the transformation used in the program VGK (Reference 2) which deals with two-dimensional flows. As for VGK any one (or more) of the wing sections may have finite trailing-edge thickness (*i.e.* a blunt base) provided such thickness is small – less than 1 per cent of the local chord, say. The treatment of a section with a blunt trailing-edge in FP is analogous to the treatment in VGK for two-dimensional flow. Sketch 2.1 indicates the overall nature of the grid for a simple wing-body configuration.

The grid employed in FP treats the wing tip in a simple way, in effect by interpolation between the tip section as specified in the input (of finite thickness) and the next 'section' outboard, which has zero thickness and camber, and corresponds to a line segment located in the $z = 0$ plane in physical space. (In the flow solver, sections at and outboard of the tip support no lift.)

In FP, the grid generator has array dimensions that provide for a maximum grid size that has 20 intervals in the r direction ($L = 22$), 36 intervals in the η direction ($M = 38$), and 160 intervals in the θ direction ($N = 162$).

Two input files are utilised by the grid generator, namely GEO.DAT and MAP.DAT. The first of these defines the wing geometry and body geometry (where there is one). The second file provides values for L , M and N , and a number of other parameters. These include parameters that control the shape of various grid lines, such as those which follow the leading- and trailing-edges out to the tip, and then break away from these edges and 'move' outboard to infinity (thereby defining a pseudo-planform), and also parameters that affect the spacing of grid lines in the y direction.

Because of the options for tailoring the grid that are provided for a user of FP, it is possible to investigate the effects of different grids on the flows obtained. Some examples indicating the effects of different grids are given in Part 2.

3.2 Flow Solver

The flow solver of FP utilises data produced by the grid generator, together with data read from an input file named FLOW.DAT, and proceeds to calculate the solution to the exact (or full) potential equation of inviscid compressible flow in three dimensions, by a method of finite-differences. The solution algorithm uses repeated iterations with 'over-relaxation'. The speed of overall convergence is improved by the facility to perform the relaxation scheme on three different levels of grid fineness. The finest grid (level 1) corresponds to the grid as produced by the grid generator. The middle grid (level 2) has half the numbers of grid intervals in each of the three coordinates (r , η , θ) of those in level 1. The coarsest grid (level 3) has the same number of grid intervals in the r and η directions as those of the middle grid, but half the number of grid intervals in the θ direction of those of the middle grid (*i.e.* one quarter the number of grid intervals of those of the finest grid). The user controls the number of relaxation iterations carried out on each grid by means of parameters in the input file FLOW.DAT. A batch of successive iterations on a particular level of grid is termed a step. A typical run commences with one or two coarse-grid steps, continues with a middle-grid step and concludes with one or more fine grid steps. Each step typically comprises one hundred or more iterations. Full convergence (when changes in the computed flow can no longer be detected) typically requires two thousand or more iterations. As well as specifying a particular number of iterations for a step, it is also possible to impose convergence criteria, and to make the termination of the run (or step) dependent on the satisfaction of these criteria. See Part 2 for further details.

Following completion of the specified numbers of iterations, the flow solver would generally be commanded (by appropriate input in FLOW.DAT) to evaluate and output a number of aerodynamic parameters. (Such evaluation may also be carried out in order to check convergence criteria.) Some of these parameters apply to a number of wing sections (these sections relate to the grid lines employed rather than to the sections input to the grid generator through GEO.DAT). Other parameters apply to the overall configuration. Flow parameters, referring to the body (if any) are not specifically determined, but assumptions are made for the variation of C_{LL} and C_{DL} over the body region to enable the overall configuration lift and drag coefficients to be calculated*. The section lift and drag coefficients are determined by integration of computed local C_p values. The overall lift and drag coefficients are then found by appropriate integrations of the section values. Because of this manner of determining drag, there is no direct way of determining the separate contributions of trailing-vortex and wave drag. Clearly, if the flow is free of shocks, the drag must be entirely due to trailing-vortex effects. It is possible to estimate the trailing-vortex drag from a knowledge of the spanwise distribution of lift, as is considered in Section 4, and such estimates, together with estimates of C_{DW} (where appropriate) can be used as a check on the drag coefficient values obtained by FP. Post-processing programs which perform calculations of trailing-vortex drag and wave drag are presented in Part 4 (Reference 12). It is recommended that the post-processing programs be utilized as a matter of routine following any run of FP or FPIBE (see Part 3, Reference 11).

* It is recommended that Part 3 (Reference 11) be consulted, and that the version of FP denoted by FPIBE, which is described therein, be used in all cases where wing-body combinations are of interest. Part 3 presents improved estimates of the lift and drag contributions of the body, as compared with the original method (FP).

In methods, such as FP, that utilise solutions of the velocity potential to calculate inviscid flows, the lift produced on a wing section corresponds to a discontinuity in the velocity potential at the trailing-edge (the only location on the section where such a discontinuity is permitted). Consequently, the finite-difference approximation to the potential equation is applied on either side of the grid surface emanating from the trailing-edge, but not across this surface. A condition of continuity of pressure across the surface is applicable, and may be utilised. In principle, in inviscid flow, application of the Kutta-Zhukovsky condition of smooth flow past the trailing-edge requires a vortex sheet to be introduced, which trails downstream from the trailing-edge. Across the vortex sheet the fluid velocity may jump (although continuity of pressure across the sheet requires the speed to be the same on either side at any point). On each side of the sheet the fluid velocity must be tangential to it. The location and form of the vortex sheet influences, and is influenced by, the rest of the flow field, and since it is a stream surface, it deforms and generally rolls up, see, for example, Reference 3. In the vortex sheet approximation employed in FP (in common with other methods of solution of the full potential equation), the trailing vortex sheet is effectively assumed to coincide with the grid surface passing through the trailing-edge. The practical significance of this assumption is that no effects of wake roll-up can be accounted for by FP, and so it must be expected to lose accuracy at relatively high lift conditions, where such rolling-up might noticeably influence the flow over the wing. In addition, details of the flow near the wing tip (where the flow is relatively sensitive to the form of the vortex wake) could not be expected to be fully reliable even at conditions of moderate lift.

A further limitation of potential methods concerns the treatment of shock waves. Rapid changes in the flow parameters, representative of shock waves, may be generated in a finite-difference solution of the full potential equation, by employing difference schemes that switch in form depending on whether the local flow is supersonic or subsonic, and which take account of the local flow direction. To ensure that mass flux is conserved when such switching is used, extra terms, having the form of 'artificial viscosity', are introduced (see Reference 4). Since the flow is potential it is isentropic, and it is not possible to model physical shock waves correctly, so when mass is fully conserved momentum is not conserved, and vice versa. Shocks which do satisfy the correct physical conditions of conservation of mass and momentum may be obtained from numerical solutions of the Euler equations of inviscid flow. Shock waves obtained from potential flow solutions in which mass is fully conserved are usually found to be stronger, in varying degrees, than the shocks in the corresponding solutions of the Euler equations (see Reference 4). An empirical difference scheme, termed 'partially-conservative', in which neither mass nor momentum is conserved, has been devised for full potential solution methods (Reference 5), and has been found to give good agreement with Euler solutions. The precise form of the 'partially-conservative' difference scheme applied depends on the values assigned to two parameters, namely the partially-conservative parameter (ALAMD in Reference 1) and the artificial viscosity parameter (EPS in Reference 1). Generally, the best results are obtained with ALAMD = 0.25 and with values of EPS in the range 0.4 to 1.0. 'Fully-conservative' and 'partially-conservative' difference schemes are both available in FP. Further details are given in Reference 1.

As an alternative to directly modelling the effects of fore and aft body shaping, the flow solver in FP incorporates a facility for incrementing the freestream Mach number by amounts that may vary across the span. The varying increments are used in conjunction with a cylindrical representation of the body geometry to provide an approximate method of allowing for the 'source-sink' effects of body shaping on the wing flow. The appropriate values for these increments are supplied to FP through input parameters in the file FLOW.DAT, and they may be determined, approximately, for any particular case, by a body-alone method such as slender-body theory or a panel method. It is important to note that the 'source-sink' effects of body shaping act to increase the component of the oncoming flow parallel to the body axis, which varies across the span. (It decreases with increasing y .) When the body is at finite incidence, simply incrementing the freestream Mach number increases both the component of the oncoming flow normal to the body axis as well as the component parallel to it. To remove the component of the increment normal to the body axis it is necessary in general to decrease the incidence and impart a change in wing twist across the span. This requires changing the input files FLOW.DAT and GEO.DAT appropriately (see Part 2). It is intended to issue a procedure for implementing the effects of body shaping by means of the 'source-sink' representation in a forthcoming Data Item.

4. COMPARISON OF FP RESULTS WITH RESULTS OF OTHER METHODS

In this Section, comparisons of FP results with results from other computational methods for inviscid flows are given. The FP results have been obtained using input files generated by FPCON (see Reference 1), with modification to these input files generally being restricted to changes in FLOW.DAT, where in some instances, the value of the artificial viscosity (EPS) in the final step has been set to 1 rather than 0.4 as produced by FPCON. (As noted in Reference 1, such an increase can help to avoid local irregularities in the computed pressures.) Also, in some instances the parameter ROVR has been reduced below the value of 1.75 produced by FPCON, either to 1.6 or 1.5, in order to avoid divergence. All the FP results presented are effectively fully converged. This is a consequence of selecting the ' C_L and/or C_D convergence' option when running FPCON to generate the input files for FP (see Reference 1, Section 3.5).

4.1 Results for Subcritical Flow about a Wing

A number of runs of FP corresponding to subcritical flow about an isolated swept tapered wing are presented here, and these results are compared with lifting-surface theory and with features known to arise on finite swept wings.

The wing geometry used is that known as the ONERA M6 wing. It is defined in Reference 6, which also presents results of inviscid flow calculations made for two supercritical test cases from a number of Euler codes, *i.e.* CFD codes which solve the Euler equations of motion rather than the velocity potential equation (see Section 3). Comparisons with these supercritical results are presented in Section 4.2.

The ONERA M6 wing has a straight-tapered planform, with $A_g = 3.8$, and $\Lambda_{le} = 30$ deg. The section shape is constant, relative to the local chord, across the span. There is zero camber and twist on all sections. The planform and section shape are shown in Figure 1.

4.1.1 Flow at low Mach number and zero incidence about M6 wing

Results from FP were obtained corresponding to $M_\infty = 0.2$ and $\alpha = 0$ and, as noted, with the input files generated by FPCON with the ' C_L and/or C_D convergence' option selected (see Reference 1). The grid layout obtained in the plane $z = 0$ is shown in Figure 1. There are no exceptional features in the grid likely to lead to inaccuracy in flow results. Values obtained from FP for the coefficients of (overall) lift and drag are very small, respectively $C_L = -0.00009$, and $C_D = -0.00087$, which may be regarded as very satisfactory, since the theoretical values are zero. The sectional coefficient values are shown in Figure 2. It is seen that C_{LL} values are very small, as they should be. Values of C_{DL} are positive inboard and negative outboard, which is a known characteristic of inviscid flow over a swept wing, see Chapter 4 of Reference 3. In integrating over the span to obtain the overall drag, the positive and negative contributions should cancel. It is remarkable that the result from FP in this case for the overall drag coefficient is as small as it is, bearing in mind that it is obtained by integration of surface pressures, and that the sectional drag coefficient values (which are also obtained by integration of pressures) have magnitudes up to nearly 0.03.

The surface pressure distribution from FP is shown in Figure 3. Upper and lower surface isobars are indistinguishable. In addition to the isobar plot, distributions of C_p at three sections, corresponding to $\eta_s = 0, 0.483$ and 0.987 are shown in Figure 3. The known centre and tip effects of a swept wing, described in Reference 3, are apparent in this figure. In Figure 4, the pressure distribution near the mid semi-span position is compared with two-dimensional flow distributions given by VGK (see Reference 2) for the M6 wing section at $M_\infty = 0.2$, one with no sweep allowance, and one with a simple allowance related to the sweep of the mid-chord line. It is seen that there is fair agreement over most of the chord between the FP distribution and that from VGK with a simple effective sweep allowance. If the variation of sweep along the chord were taken into account, better agreement would be obtained.