



Full-potential method for three-dimensional wings and wing-body combinations – inviscid flow

Part 4: Evaluation of trailing-vortex drag and wave drag components

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

PART 4: EVALUATION OF TRAILING-VORTEX DRAG AND WAVE DRAG COMPONENTS

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

PART 4: EVALUATION OF TRAILING-VORTEX DRAG AND WAVE DRAG COMPONENTS

1. INTRODUCTION

This Item presents programs that evaluate the trailing-vortex drag and wave drag components corresponding to any prior run of the full-potential method presented in References 1, 2 and 3. Inviscid flows about wing-alone and wing-body combinations are dealt with. In addition to the drag components the programs provide a value for the overall lift. The programs use as input one of the output files produced by a run of the full-potential program (preferably a fully-converged run), and for this reason they are termed 'post-processing' programs for the full-potential method.

As explained in Section 3, the post-processing programs in this Item utilize a wake flow model that enables the overall lift and trailing-vortex drag for a wing-body combination to be determined solely from its wing flow parameters. The wave drag calculations also only utilize wing flow parameters. As a consequence, so far as the results from the post-processing programs are concerned, it makes no difference whether the input file which they utilize is generated by a run of the original FP program (References 1 and 2) or by the variant FPIBE (Reference 3), which, for a wing-body combination, provides improved estimates of the body contributions to the overall lift and drag relative to the original FP program. The calculations of the body effects in the present Item are more soundly based than those of both FP and FPIBE, whilst determination of the wing contributions to drag avoids the errors associated with numerical integration of pressure around the wing surface. For simplicity, in the examples given in this Item, comparisons of results from the post-processing programs are made only with results from FPIBE, not with FP. Also, for convenience, the data files used as input for the post-processing programs in these examples have been generated by runs of FPIBE, rather than FP.

As well as being generally more reliable than FPIBE and FP for overall lift and drag, use of the present Item is advisable because knowledge of the separate components of drag, namely trailing-vortex drag and wave drag, is often of practical value. For example, it helps in assessing the importance of a particular shock wave system and, in the wing design process, it may help in assessing the relative merits of various wing twist distributions, and assessing different choices of wing section.

The principles of evaluation of the overall lift and the trailing-vortex and wave drag components employed in this Item are given in Section 3. The detailed use of the programs is presented in Section 4. Some examples relating to a number of wing and wing-body configurations are given in Section 5, and remarks on the relevance of the inviscid flow solutions to real viscous flows are made in Section 6. Concluding comments, including remarks on accuracy, are in Section 7.

1.1 PROGRAM ACCESS

The files required to run FP and all 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 or FPIBE, and the post-processing programs, carry out the following five 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.
- (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 FP be consulted in detail.

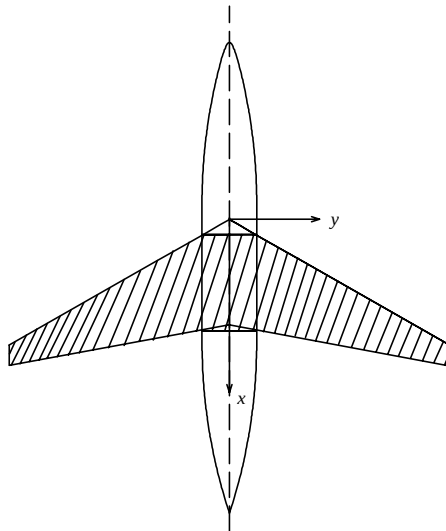
2. NOTATION

In the Notation used for FP and FPIBE, lengths are made non-dimensional by division by c_0 , the centre-line chord, see below. Quantities notionally of length (other than c_0) listed in this Section, such as c and s are thus non-dimensional, having been made so by division of the corresponding length quantities by c_0 . Similarly, the reference wing area S is also dimensionless, having been made so by dividing the corresponding actual area by c_0^2 . Note that alternative wing reference areas are defined and referred to in Parts 1 and 2, but in this Item only the reference area denoted in Parts 1 and 2 by S_1 is used, see Sketch 2.1. Here it is denoted simply by S .

A	(gross) wing aspect ratio, $= 4s^2 / S$
C_D	overall drag coefficient, ($= C_{DTV} + C_{DW}$ in this Item)
C_{DTV}	trailing-vortex drag coefficient
C_{DW}	overall wave drag coefficient
C_{DWL}	local wave drag coefficient, based on local chord
C_L	overall lift coefficient
C_{LL}	local lift coefficient, based on local chord
C_p	pressure coefficient
C_{psh}	pressure coefficient at shock upstream location
c	local wing chord
$\bar{c}$	mean geometric chord, $\bar{c} = S / 2s$
c_0	centre-line chord, formed (if necessary) by continuing leading edge and trailing edge of wing, near root, by straight lines to $y = 0$

D_{TV}	trailing-vortex drag
L	overall lift
M_{∞}	freestream Mach number
M_{Lnsh}	Mach number corresponding to velocity component normal to shock wave (just upstream of shock wave)
n	coordinate along (local) outward normal to vortex trace
R	body radius (varies with x)
R_t	body radius at x -location corresponding to wing-tip trailing edge
S	(gross) 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 2.1)
s	wing semispan, measured from configuration centre-line (<i>i.e.</i> not from wing root in case of wing-body)
s'	semispan of wing vortex trace in Trefftz plane (see Sketch 3.1)
V_{∞}	freestream speed
w'	upwash at wing vortex trace in Trefftz plane
x, y, z	Cartesian coordinates in physical space (non-dimensional)
y', z'	Cartesian coordinates in Trefftz plane (see Sketch 3.1)
ΔC_{DTV}	excess trailing-vortex drag coefficient
α	incidence angle, angle of inclination of x axis to freestream direction (positive nose up), deg
φ	perturbation velocity potential
Λ	sweep angle (positive for sweepback), deg
η	relative spanwise position, $\eta = y/s$
η'	relative spanwise position in Trefftz plane, $\eta' = y'/s'$
$\tilde{\eta}'$	integration variable corresponding to η'
η_c	value of η of crank section
<i>Suffices</i>	
B	denotes vortex trace of body (relates to Trefftz plane)
BA	denotes body alone

le	denotes value at leading edge
sh	denotes shock wave
te	denotes value at trailing edge
W	denotes vortex trace of wing (relates to Trefftz plane)
WB	denotes mutual interference of wing and body



Sketch 2.1 Illustration of reference wing area S (denoted by S_1 in Parts 1 and 2)

(Note that S is made non-dimensional by division by c_0^2 .)

3. PRINCIPLES OF EVALUATION OF TRAILING-VORTEX DRAG AND WAVE DRAG

This Item adopts the framework presented in Reference 4 for the calculation of the drag of wing-body combinations at subsonic speeds. This framework caters for experimental and calculated flows (either viscous or inviscid). It is based on the idea that the drag of the wing may be synthesised from three separate components, namely the drag due to boundary-layer momentum deficit or viscous drag, the trailing-vortex drag (associated with the rate of work done in generating the trailing vortices), and the wave drag (due to embedded shock waves). Here the situation is simplified as FP and FPIBE are calculation methods for inviscid flow, so there is no viscous drag. It has been shown (Reference 5) that the errors implied by the synthesis are 'second order' with the error terms being of the order of the squares and products of the individual drag coefficients. A critical comparison of the results of the method with those obtained from direct measurements for shock-free flows has indicated an underestimate of drag coefficient by up to 0.0008 in the range of Mach numbers 0.6 to 0.8, see Reference 4. These discrepancies are attributed in Reference 4 to inadequate modelling of the viscous drag, and thus would not apply in this Item. However, there has been no critical assessment of the method as it applies to inviscid flows.

3.1 Trailing-Vortex Drag

Trailing-vortex drag is calculated using a method based on the ideas of linearised theory and thus ignores the effects of rolling-up and downward deflection of the trailing-vortex sheet. There is assumed to be no interaction between the trailing vortices and the entropy layers downstream of any shocks. The implications of this assumption are discussed by Lock in Reference 5. The flow is thus assumed to be irrotational and hence may be defined by a velocity potential. This assumption is of course central to (and thus compatible with) the use of the full-potential flow method.

The perturbation potential, ϕ , is then written as

$$\phi = \phi_{BA} + \phi_{WB}, \quad (3.1)$$

where suffices *BA* and *WB* refer to the body alone and to the mutual interference between the wing and the body. The Cartesian coordinate system used is shown in Sketch 3.1.

According to wing theory (see Reference 6, for example), lift and trailing-vortex drag may be written as

$$L = \rho_{\infty} V_{\infty} \int_{B, W} \phi \cos \bar{\theta} dt, \quad (3.2)$$

$$\text{and} \quad D_{TV} = \frac{1}{2} \rho_{\infty} \int_{B, W} \phi \frac{\partial \phi}{\partial n} dt. \quad (3.3)$$

In each case the integration is taken around the trace of the trailing vortices (simply termed vortex trace) of the body (suffix *B*) and the wing (suffix *W*) in the Trefftz plane. Here n denotes the outward normal to the vortex trace, whilst t is the length of the arc along it and $\bar{\theta}$ is the angle between the normal n and the z axis.

To apply these equations the geometry of the vortex trace and the distribution of vortex strength across the vortex trace need to be known. Reference 4 presents two flow models, termed there Model A and Model B. Model B is particularly simple in that the body is neglected, and the wing part of the vortex trace is extended to the body centre line. (The lift per unit span over the extended part is set equal to its value at the body side.) In the Model A scheme of Reference 4, which is adopted in this Item, the vortex strength and vortex trace are determined using the assumption that the streamlines emanating from the wing trailing-edge have the same form as in the non-lifting case. The free vortex lines aft of the trailing edge coincide with these streamlines. For a wing-alone these streamlines are straight and parallel to the x axis, and determination of the lift and drag is straightforward once the spanwise distribution of lift is known. For a wing-body the

assumption amounts to taking the wing-body streamlines (aft of the trailing edge) to have the same form as if the wing were absent, so they are the same as those about the body-alone at zero incidence. Slender-body theory then readily provides the relationship, for a particular streamline, between its point at the trailing edge and its point in the vortex trace. In this Item it is also assumed that the body is closed, and that the wing is essentially planar (in a plane $z = \text{constant}$). These assumptions and their implications are also presented in Reference 7.

Each streamline in the flow about an axially symmetric body at zero incidence must lie in a plane $\theta = \text{constant}$. For any streamline passing through the trailing edge, it is found (see Reference 4) that the radial coordinate far downstream of the body, r , and the radial coordinate at the trailing edge, r_{te} , are related by

$$r^2 = r_{te}^2 - R^2. \quad (3.4)$$

Here R is the body radius at the x -location corresponding to the point on the trailing edge under consideration. In the case where the wing plane contains the body axis (mid mounted wing), the vortex trace is a straight line, and has a semispan, s' , given by

$$s' = (s^2 - R_t^2)^{1/2}. \quad (3.5)$$

Here R_t is the body radius at the x -location corresponding to the trailing-edge of the wing tip. In this case, a streamline passing through the trailing edge and having the value η there for its relative spanwise coordinate, has a relative spanwise coordinate in the trace equal to η' , where η' and η are related by

$$\eta'^2 = (\eta^2 - (R/s)^2) / (1 - (R_t/s)^2). \quad (3.6)$$

Expressions for the overall lift and trailing-vortex drag coefficients are then determined as

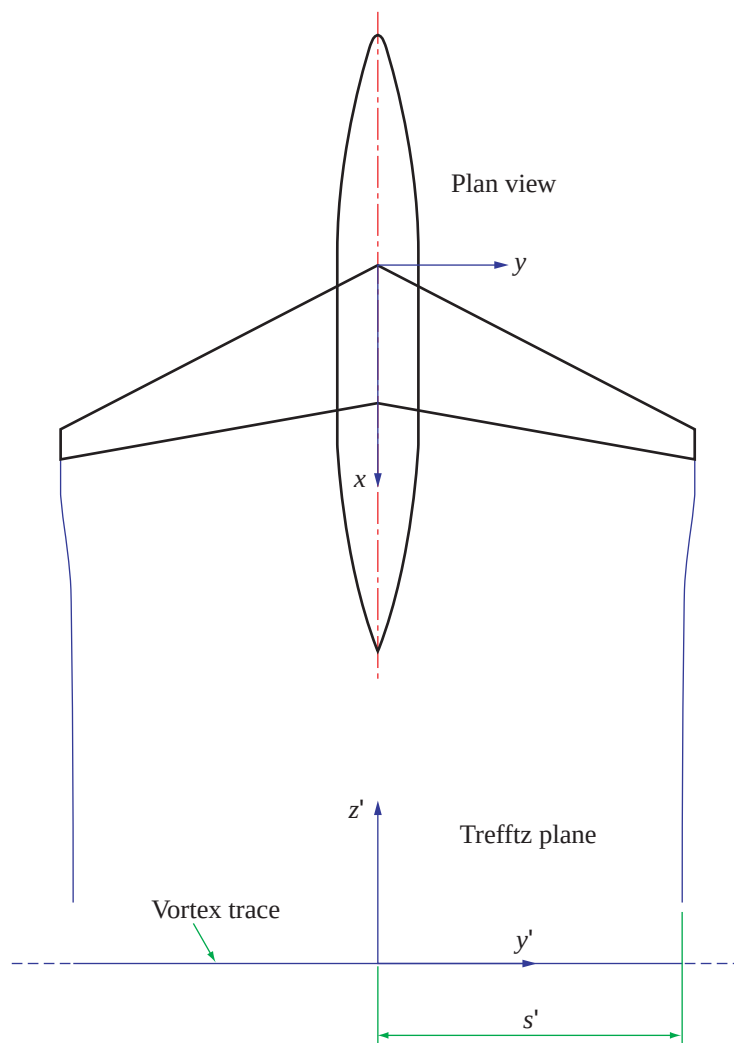
$$C_L = \frac{L}{\rho_\infty V_\infty^2 s \bar{c}} = \frac{s'}{2s\bar{c}} \int_{-1}^{+1} C_{LL}(\eta) c(\eta) d\eta, \quad (3.7)$$

$$C_{DTV} = \frac{D_{TV}}{\rho_\infty V_\infty^2 s \bar{c}} = \frac{-s'}{4s\bar{c}} \int_{-1}^{+1} C_{LL}(\eta) c(\eta) \frac{w'(\eta')}{V_\infty} d\eta. \quad (3.8)$$

In these equations $C_{LL}(\eta)$ and $c(\eta)$ are to be considered functions of η' , where the relationship between η and η' is given by Equation (3.6).

The induced upwash, w' , is given by

$$\frac{w'(\eta')}{V_\infty} = \frac{1}{2\pi A} \int_{-1}^1 \frac{d}{d\tilde{\eta}'} \left(\frac{C_{LL}(\eta) c(\eta)}{\bar{c}} \right) \frac{d\tilde{\eta}'}{(\tilde{\eta}' - \eta')}. \quad (3.9)$$



Sketch 3.1 Plan view and Trefftz plane corresponding to approach termed Model A

(Note that the amount by which s' is less than s is exaggerated in the sketch.)

In general, the coefficient of trailing-vortex drag of a well designed wing-body combination is close to the minimum value for a planar wing (at least when operating close to the design conditions). This minimum is $C_L^2/\pi A$, see, for example, Reference 6. As a result, the trailing-vortex drag is sometimes expressed in terms of the amount by which it exceeds this minimum, to which the term 'excess trailing-vortex drag' is applied. The excess trailing-vortex drag coefficient, ΔC_{DTV} , is given by

$$\Delta C_{DTV} = C_{DTV} - (C_L^2/\pi A). \quad (3.10)$$

In Reference 8 a comparison is made for a number of wing-body configurations of lift and trailing-vortex drag calculated using both Model A and Model B assumptions. Because a given distribution of lift per unit span is spread over a smaller vortex-trace span in the Model A scheme than in the Model B scheme, it is found that the overall lift is consistently somewhat smaller for Model A than Model B (generally by no more than a few per cent). The trailing-vortex drag values from the two schemes are barely distinguishable,

apparently because the larger magnitudes of induced upwash resulting from the smaller vortex-trace span in Model A are almost exactly compensated by the lower overall lift. The Model A assumptions are more soundly based than those of Model B. Also, the lift coefficient values from use of the Model A scheme are found to be closer to those derived from correlations of panel method calculations (see Reference 8) than are those from Model B. Thus, the Model A scheme is preferred to the Model B scheme, and is adopted in this Item.

Errors in C_{DTV} arise from oversimplification in modelling the trailing-vortex sheet, principally in regions close to the body and close to the wing tips. Differences from the two approaches (Model A and Model B), are small, as noted above, and this suggests that the variations in the value of C_{DTV} due to effects from the uncertainty in regions near the body are small, but the effects of deficiency of modelling the flow in the region of the wing tips are less easily assessed. The main deficiency, according to Reference 5, is due to lack of representation of the rolling-up of the trailing vortices. However, the effects of this rolling-up are concentrated near the wing tips where the wing is relatively lightly loaded. For wings of moderate to high aspect ratio it is believed that the effects may be ignored (Reference 5).

A further effect on C_{DTV} arises due to the downward deflection of the trailing-vortex sheet which is not represented in the linear approach given here (see Reference 9). Lock (Reference 5) showed that this effect could reasonably be ignored for wings of high aspect ratio, although for wings of low aspect ratio this was not necessarily so.

For a given overall lift, errors in C_{DTV} also arise from errors in the spanwise lift distribution. The present method may be used to assess such errors in C_{DTV} , and it is found that, for the range of errors in spanwise lift distribution likely to occur, the resulting errors in C_{DTV} should be negligible.

3.2 Wave Drag

The wave drag component is calculated using the approximate method developed by Lock initially for aerofoils but later extended by him to deal with wings. This method and the corresponding computer program are presented, together with examples and a detailed evaluation, in Reference 10. The method may be utilized with either calculated or measured wing surface pressure distributions given at a number of streamwise sections across the span. From these pressures the method determines the spanwise distributions of shock sweep and shock strength (defined by the Mach number of the fluid velocity component just upstream of and normal to the shock, $M_{L_{nsh}}$) for each shock identified. For each such shock, the decay of its strength in the direction normal to the wing surface is expressed in terms of the streamwise curvature of the wing surface on the assumption that the flow is locally two-dimensional. This information on the shock waves is then used to yield (for each shock) the lateral distribution of wave drag and, by integration of this, the overall wave drag. There are two variants of the method, which in Reference 10 are denoted respectively as the 'first-order method' and the 'improved method'. The latter is denoted in this Item as the second-order method. In the first-order method the decay in the shock strength (at a particular spanwise position) in the direction normal to the wing is taken to depend on the wing surface curvature only at that shock location. In the second-order method the fact that this decay should depend on the shape of the surface for some distance ahead of the foot of the shock is taken into account, by means of an analysis that utilizes a number of reasonable assumptions.

A number of requirements must be fulfilled in order to make use of the method and computer program of Reference 10 to determine the wave drag and its spanwise distribution. Thus, any shock dealt with must be present at a minimum of four spanwise locations (*i.e.* in FP at four consecutive streamwise grid lines). As a consequence no wave drag prediction can be obtained corresponding to the conditions of the onset of wave drag. Also, the wing should be formed from smooth aerofoil sections for the method to be applicable.

Assessments of the accuracy of the method (Reference 10) suggest that moderate amounts of wave drag are usually overestimated by about 10 percent, but may occasionally be up to 20 percent high. When the wave drag is small the overestimate in wave drag coefficient may be up to 5×10^{-4} . These assessments are based on applications mainly to wings of high aspect ratio and moderate sweep, but do include one wing of lower aspect ratio (namely 4) and higher sweep ($\Lambda_{le} = 40$ deg). The assessments utilize observed pressure distributions, and are therefore applicable to viscous flows. However the derivation of the method relies on approximating the shock strength in the inviscid flow region, and so no further errors or uncertainties should be expected when the method is applied to inviscid flow results, as in the present case, rather than to viscous flow results.

4. USE OF THE TRAILING-VORTEX DRAG AND WAVE DRAG PROGRAMS

A batch program, named PPDRAG.BAT, runs a number of programs in sequence to perform four tasks as follows:

- data extraction,
- calculation of coefficients of lift and trailing-vortex drag,
- calculation of wave drag coefficients,
- collection of data from the preceding programs, and presentation of these data.

The data extraction program operates on either the file FLOW.RES (produced by FP) or BFLOW.RES (produced by FPIBE), to obtain the relevant geometry and flow data, and arranges these data in an appropriate manner for use by the subsequent programs. The wave drag calculation programs are in two blocks, the first of which deals with the flow over the upper surface and the second of which deals with the flow over the lower surface of the wing.

In addition to coefficients of lift and trailing-vortex drag, a run of PPDRAG.BAT also gives the wave drag coefficients associated with each wing surface, and values for the total drag coefficient (trailing-vortex drag plus wave drag). Results corresponding to both the first-order and second-order wave drag calculation procedures are produced. Overall lift and drag coefficients and component drag coefficients are given in the annotated file OVDRA.G.RES. Spanwise distributions of wave drag are given in the files WAVEPRUS.DAT and WAVEPRLS.DAT for the upper- and lower-wing surfaces respectively.

4.1 Trailing-Vortex Drag Programs

The program VORTD.FOR implements a numerical scheme for evaluating the lift and trailing-vortex drag according to the Model A approach described in Section 3.1. The principal data required by VORTD.FOR are the local lift coefficient for each spanwise grid location and a number of wing geometry parameters, namely the corresponding local chord values and the wing semispan and reference wing area. These data are available in a number of the files produced by a run of FP or FPIBE. However, the input data for VORTD.FOR are obtained indirectly by use of a further program (named PRODVORT.FOR) specifically written for this purpose. This program effectively extracts the required data from the file named FLOW.RES (which is one of the output files of FP), or from BFLOW.RES (which is the corresponding output file of FPIBE). These data are then written (without annotation) to an output file named VORT1.DAT. The same data are also written in annotated form to a file named VORTCH.DAT. An error message is output if the required data are not found in the file FLOW.RES (or BFLOW.RES). This would happen if the run of FP (or FPIBE) intended to generate the input file FLOW.RES (or BFLOW.RES) had diverged, see Reference 3.

4.2 Wave Drag Programs

Having determined the coefficients of lift and trailing-vortex drag, the batch program deals with shock waves and wave drag associated with the flow over the upper surface of the wing, and then with shock waves and wave drag associated with flow over the lower surface of the wing.

The principal program used to implement the approximate method of wave drag calculation described in Section 3.2 is essentially the one referred to as ESDUpac 8703 in Reference 10. The only changes introduced are ones to simplify file handling. The modified program is named WAV87003.FOR. Two input files are read by this program. One provides a number of overall wing geometry parameters and, for each spanwise grid section, the wing surface coordinates (for either the upper surface or lower surface, as relevant) and the leading-edge and trailing-edge sweep angles. The second file provides (for each shock detected) values for the chordwise location of the shock, ξ_{sh} , and the corresponding value of C_{psh} , for each value of η at which the shock is detected. Separate runs of the program are needed for the upper- and lower-surface flows.

The input file providing the wing geometry data to WAV87003.FOR is named WAVE.GEO, and that giving the shock wave data is named SHOCK.DAT. A program, named PRODWAV.FOR, has been written to produce data files of the required forms. It uses as input the file named FLOW.RES or BFLOW.RES, (which are output files produced by runs of FP or FPIBE). This program generates files named GE87003U.DAT and GE87003L.DAT, which are respectively the wing geometry data files for the upper and lower surfaces of the wing, and ETAXCPU.DAT and ETAXCPL.DAT, which are the corresponding shock wave data files.

PRODWAV.FOR incorporates a procedure for detecting the presence of shock waves. This examines the pressure at each spanwise grid section in turn. The routine that does this shock detection is the same as the one incorporated for this purpose in the aerofoil program VGK (see Reference 11). Since there may be more than one shock detected at any spanwise location (on either or both the upper- or lower-surface), and also because it is necessary to specify how shocks detected at different spanwise locations relate to one another, a further program, named SORTSHOCKS.FOR, is run to sort the data from PRODWAV into data for identifiable shocks. All the programs needed for both upper-and lower-surface shocks are incorporated into the batch program PPDRA.G.BAT. As stated, coefficients for overall lift, drag, trailing-vortex drag and wave drag are output to the annotated file OVDRA.G.RES, and results for both the first-order and second-order wave drag procedures are presented.