



**Full-potential method for
three-dimensional wings and wing-body
combinations
Part 6: Full-potential with frozen
boundary layer**



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

PART 6: FULL-POTENTIAL WITH FROZEN BOUNDARY LAYER

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

Part 6: Full-potential with frozen boundary layer

1. INTRODUCTION

This is the sixth part of the series of Data Items^{1,2,3,4,5} dealing with the Full-Potential method FP for three-dimensional wings and wing-body combinations. One of the advantages of the FP 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 Data Item provides an enhancement to this process by adding a frozen boundary layer to the wing surfaces in the form of a displacement thickness to take account of viscous effects.

As described in ESDU 02013¹ the consideration of viscous effects is assessed using VGK⁶ on the outer wing section of the W4 wing with a simple correction for sweep. ESDU 11007 describes an alternative procedure for implementing viscous effects using a method described by Powell⁷ with corrections for sweep. This is a subsonic method with compressibility corrections and calculates the boundary-layer characteristics for shock-free conditions. It has also been enhanced to give an improved calculation of sectional viscous drag. The process is set up to provide a pre-processor to FP to routinely calculate and add the displacement thickness to the wing-section geometry. The process involves using the FP inviscid wing-geometry file with additional information such as Reynolds number and upper- and lower-surface transition locations. The process produces a new FP wing geometry that includes displacement thickness, section boundary layer information and a viscous drag estimate.

A detailed description of the use of the pre-processor program is given in Section 3. Comments on the accuracy and limitations are in Section 4. The principles of the method are given in Section 5. The validation of the method is discussed in Section 6.

1.1 Program Access

The files required to run the frozen boundary layer pre-processor programs on a PC are to be found in the folder (or directory) name FPFBL1.

Executable forms of the programs are included, so no Fortran compiler is required. To set up the MATLAB Graphical User Interface (GUI) 'fblayer' follow the installation instructions given in the READMEFBL1.

To run the frozen boundary-layer the pre-processing programs, 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 FPFBL1 to this working directory.
- (4) Read the contents of the file READMEFBL1 (which is one of the files copied), using an editor or other suitable application.
- (5) Proceed according to the directions given in that file.

2. NOTATION AND COORDINATE SYSTEM

In the Notation used for FP and FPIBE (ESDU 02014), lengths are made non-dimensional by division by the dimensional value of centre-line chord. **Quantities notionally of length listed in this Section, such as l , s , x , y and z are dimensional.**

C_D	drag coefficient
C_{DF}	skin friction drag coefficient
C_{DFuse}	fuselage drag coefficient
C_{DS}	notional section drag coefficient per surface (upper or lower)
C_{DV}	viscous drag coefficient
C_{DW}	wave drag coefficient
C_{Dwing}	wing viscous drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
c	wing chord
c_{nom}	nominal wing chord (RAE 5241)
c_0	centre-line chord
D	drag
H	boundary-layer shape parameter
H_T	transformed boundary-layer shape parameter
H_{bar}	transformed boundary-layer shape parameter
l	length
M	Mach number
M_e	local Mach number at edge of boundary layer
M_∞	freestream Mach number
Re	Reynolds number
r	recovery factor

s	wing semi-span
U	flow velocity
U_e	velocity at edge of boundary layer
x	distance along wing streamwise chord, downstream from leading edge
y	distance along wing span from centre-line
y_{sect}	y/c_0
z	vertical distance from x y plane
α	incidence
β	angle between limiting and external-flow streamlines
Δ	difference
$\Delta C_{Dvortex}$	lift dependant drag above ideal elliptic
δ^*	boundary-layer displacement thickness
δ_1	boundary-layer displacement thickness of flow in direction of external flow streamline
θ	momentum thickness
θ^s	momentum thickness of flow parallel to wing trailing edge
θ_{11}	component of boundary-layer momentum thickness [*]
θ_{12}	3D component of boundary-layer momentum thickness [*]
θ_{21}	3D component of boundary-layer momentum thickness [*]
θ_{22}	3D component of boundary-layer momentum thickness [*]
Λ	wing sweep
ϕ	angle between the external-flow streamline and normal to leading edge
ν	kinematic viscosity
ρ	density
η	y/s
τ	angle between external-flow vector and vector normal to wing trailing edge or trailing-edge angle parameter.

* defined in Reference 12

Suffices

<i>MID</i>	mid chord
<i>te</i>	trailing edge
<i>V</i>	viscous
<i>2D</i>	two dimensional
<i>3D</i>	three dimensional
∞	far downstream or freestream

3. DESCRIPTION AND USE OF PROGRAM THAT PRODUCES INPUT FILES FOR FP

The process to produce a wing with a frozen boundary layer involves running a suite of three programs. The first program 'fpfblout' reads in the GEO.DAT file created using the procedure described in Reference 2 and a VISC.DAT file which contains the following:

Mean chord based on a centre-line chord of unity,
Reynolds number based on mean chord,
Upper surface transition location in terms of x/c ,
Lower surface transition location in term of x/c ,
Freestream Mach number.

An example of a typical VISC.DAT file is shown below

```
0.541601 6000000.0 0.05 0.05 0.78
```

Program 'fpfblout' untwists and interpolates each section of the wing to a 32 pivotal point distribution and produces an input file for the swept Powell method called 'fblcalc'. The process is completed by running program 'fblfpout' which produces a file called geopivfb.dat which is the wing plus frozen boundary layer geometry file in a format suitable for FP. This wing geometry file is composed of untwisted, 65 pivotal point section coordinates with the value of input twist adjusted to match that of the starting wing geometry file.

Several other files are produced and they are as follows:

ndsection.dat

Contains detailed information on the interpolation of each section to 32 pivotal points which is part of the input for the swept Powell method.

bloutput

Main output file containing details of the boundary layer for each section at zero incidence.

drag.dat

Contains local sectional viscous drag and total wing viscous drag.

sepsummary

Contains details of run messages and separation locations.

The program suite can either be run using a 'C:\ Command Prompt' window by typing runfbl.bat or by using a MATLAB Graphical User Interface (GUI) 'fbplayer'. Using the first option the user must set up the visc.dat file before starting to run the process.

For the MATLAB GUI the window shown in [Example 1](#) is displayed where the values for mean chord, Reynolds number, wing transition locations and Mach number are entered by the user. Note that for this procedure the value of the Reynolds number entered is divided by one million, see [Example 2](#).

The screenshot shows a software window titled "fblayer" with a subtitle "Frozen Boundary-Layer Generator". Inside the window, there is a section labeled "Input Data" containing several input fields: "Mean Chord", "Reynolds Number" (with a "million" unit label), "Wing Transition" (with sub-labels "Upper x/c" and "Lower x/c"), and "Mach number". Below these fields are three buttons: "Calculate", "Reset", and "Analysis". The text "CD wing value" is displayed in the center of the window.

Example 1

Once all the values have been entered click the “Calculate” button and a C_D wing value will be displayed when the run is completed. Further output files including the wing plus frozen boundary layer geometry are also available. If the user wishes to input a new set of values then click the “Reset” button making sure that the output files are renamed by the user first or they will be overwritten.

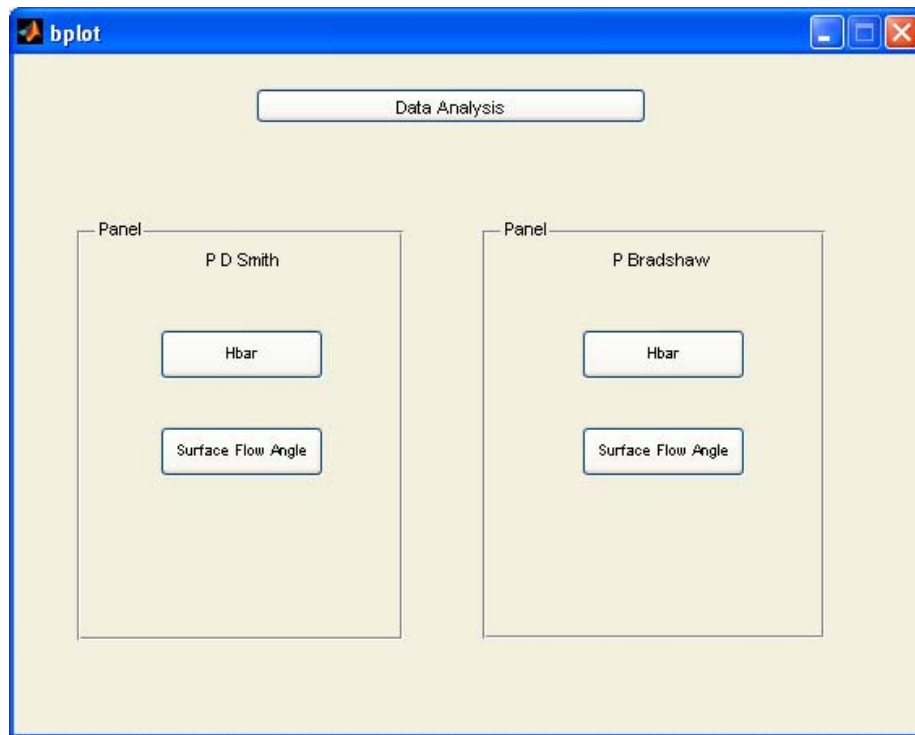
The screenshot shows a software window titled "fblayer" with a subtitle "Frozen Boundary-Layer Generator". Inside the window, there is an "Input Data" section with the following fields and values:

Parameter	Value	Unit
Mean Chord	0.541601	
Reynolds Number	6	million
Wing Transition	Upper x/c: 0.05, Lower x/c: 0.05	
Mach Number	0.78	

Below the input fields, there is a "Calculate" button. Below that, the result "CD wing= 0.007401" is displayed. At the bottom, there are "Reset" and "Analysis" buttons.

Example 2

Once the run is complete there is an option to have a quick look at some of the key boundary-layer parameters to get an initial indication of the health of the boundary layer. This option is activated by clicking the "Analysis" button which opens a new window as shown in [Example 3](#).



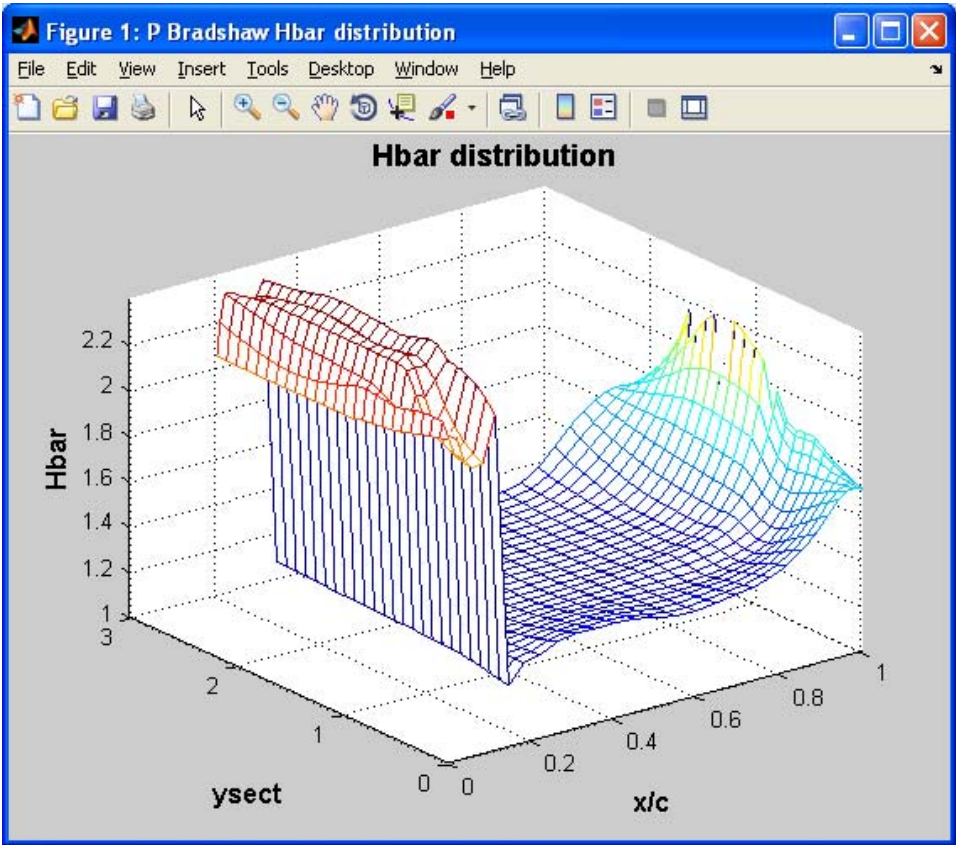
Example 3

By clicking the “Data Analysis” button, data from the main output file ‘bloutput’ is sorted to produce arrays of the upper-surface transformed boundary-layer shape factor, H_T or H_{bar} and local flow angle at the surface ($\phi + \beta$) and “Select Plot” appears when the data are ready for plotting as shown in [Example 4](#).

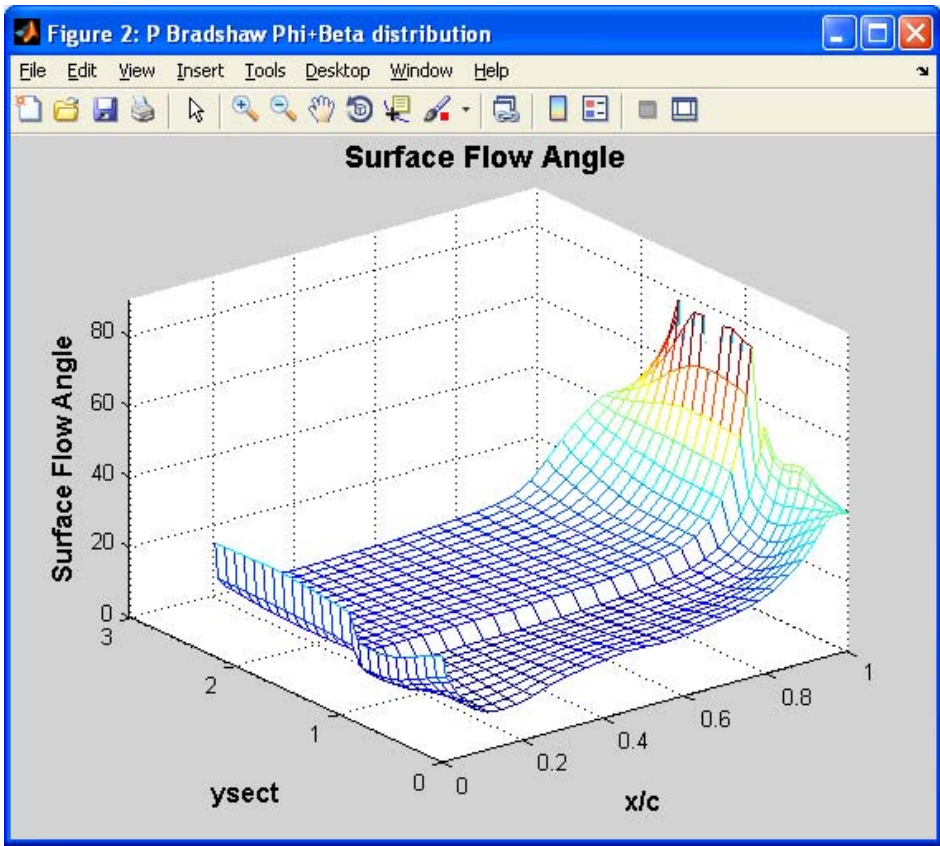


Example 4

Two sets of swept boundary-layer parameters are available which are denoted “P.D. Smith” (Reference 10) and “P. Bradshaw” (Reference 11). A more accurate Bradshaw calculation is only run when a converged solution has been calculated by Smith. For cases when the Smith method fails to obtain a converged solution the Bradshaw values are set to zero. As discussed in Section 6, comparisons of various boundary-layer parameters have shown that the Bradshaw method gives a better match than “P.D. Smith” with experiment, particularly the transformed boundary-layer shape factor which can provide a useful indicator of the probability of flow separation. When Smith fails to converge it also indicates the possibility of flow separation. By clicking the “ H_{bar} ” and “Surface Flow Angle” buttons, new windows are opened displaying a mesh plot as shown for the Bradshaw results in Example 5 and Example 6. The mesh plots give the chordwise distribution of H_{bar} and Surface Flow Angle for each spanwise location. For this example, the value of H_{bar} in the laminar part of the boundary layer is above 2 (Example 5) followed by a reduction to a level of 1.1 aft of the fixed transition at $x/c = 0.05$. The values of H_{bar} and Surface Flow Angle increase at the start of the rear adverse pressure recovery and their levels obtained at or close to the trailing edge should be monitored as an indication of the health of the boundary layer. For H_{bar} , values approaching 2.2 and above will result in separation and therefore caution should be taken for values above 2. For Surface Flow Angle, separation occurs when 90 degrees is reached, therefore caution should be taken for values above 80 degrees.



Example 5



Example 6