

Stephen Conway

ffatrans
**A Transition Prediction Program for
Aerofoils**



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Abstract

ffatrans predicts regions of transition on 2D and 2.5D aerofoil sections using boundary layer and stability analysis. It uses RANS solutions from the Edge solver as a start point. Transition is ramped over a distance computed using a transition length model. An intermittency function is used to model the growth of turbulence.

Nomenclature

γ	Intermittency function
X	Starting point on aerofoil surface
λ	Extent of transitional region
X_t	Location where flow is considered fully turbulent
X_{tr}	Location of transition
ΔX	Overall length of transition region
Re	Reynolds number
U_e	Tangential velocity at boundary layer edge
ν	Kinematic viscosity
μ	Dynamic viscosity
ρ	Density
C_p	Pressure coefficient

1 Introduction

Traditionally the modelling of transition on aerofoils in RANS solvers is accounted for by a simple switch. In most cases the location of transition is input by the user at a single point on the aerofoil surface. This location is then interpreted by the RANS solver as the location where laminar flow becomes turbulent. It has been shown however that using the pressure data obtained from a RANS solution on the aerofoil surface as input to a boundary layer computation is of sufficient accuracy as to enable one to predict the location of transition using a suitable stability analysis [6]. In order to perform the transition prediction a program has been developed which uses a RANS solution from the Edge solver [3] as input to a boundary layer solver - in this case the FOI developed solver B13D - and a stability solver. The transition prediction has been constructed in such a way that it can either be called at a predefined iteration from within the Edge solver or as a stand-alone application. Two stability methods are available for the transition prediction, a database method developed by ONERA and a local linear method (NOLOT) [4].

Some extra input is required to carry out the coupled transition prediction. An extra mesh geometry file is required which contains only the aerofoil surfaces to be considered in the transition prediction. This geometry file is "cut" from the original geometry. If we consider the example of a high-lift wing configuration, this can mean that the slat cove should be excluded from the cut geometry. Each time the transition prediction is performed the RANS solution is interpolated onto the cut geometry and the subsequent pressure distribution is used as input to the boundary layer solver. The user has two options when using the interpolated RANS result: he can either opt to use skin friction data to check for laminar separation on the surface or he can opt to let the boundary layer solver detect separation. Input data to the stability solver is obtained as a result of the boundary layer analysis. A user defined limiting N-factor is used to determine if transition occurs on each of the surfaces under consideration. If the limiting N-factor is exceeded the location of the start of transition is obtained at this point. The extent or length of the transition region is then obtained and exported back to the grid file used in Edge according to the procedure outlined in this report. This cycle is repeated until satisfactory convergence of the integrated forces has been obtained and until the points of transition have reached a stable location.

2 Running *ffatrans*

To run *ffatrans* the user needs simply type

```
> ffatrans file.ainp
```

where *file.ainp* is the input file containing all necessary parameters to run the program. A typical input file is given in the appendix. A total of 18 parameters are required to run the program. The parameters are detailed below.

2.1 The Input File

The input file to *ffatrans* consists of the following parameters in alphabetical order.

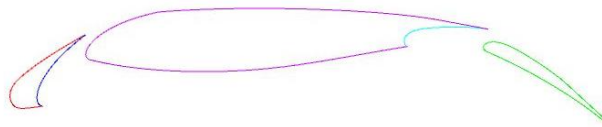
CFBL3D	Name of the input file for the boundary layer solver
CFBLEX	The path to the boundary layer solver executable
CFIEDG	The <i>.bedg</i> file to be updated with the new transition data
CFIMSH	Cut <i>.bedg</i> file containing the boundaries to be included in the stability analysis
CFIPOS	Interpolated <i>Post.bout</i> file from Edge. Used if ICFOPT = 1
CFISOL	The interpolated Edge solution file
CFSTAB	Name of the input file for the stability solver
CFSTEX	The path to the stability solver executable
ICFOPT	Method used for detecting laminar separation. = 0 then boundary layer solver detects separation. = 1 laminar separation is obtained from <i>Post.bout</i>
ICUT	The direction of the cut plane used in producing CFIMSH
ITLMC	A constant used in Walkers transition length model
MAXWAD	The maximum laminar distance normal to the wall. Beyond this distance the flow is turbulent
NCFTRA	T-S N-factor at which transition starts
NPART	Number of partitions in the mesh. Used when parallel Edge computations are to be performed
NTSTRA	Cross flow (or envelope) N-factor at which transition starts
OMEGA	Used if Edge is run in rotating mode
SWEEP	The sweep angle of the aerofoil for 2.5D calculations

2.2 Preparing the Input

The *ffatrans* program updates the existing edge mesh file, *file.bedg* with the newly computed transition locations and lengths. In order to do this the file must contain the *laminar_turbulen*, *near_wall_point* and *wall_distances* data sets. These datasets are added by either running the Edge preprocessor and setting the **ITURB** parameter to 2 for a turbulent computation and choosing a turbulence model which requires the distance to the wall (e.g Menter SST) or by running the *ffa* program *transition* on an existing *.bedg* file with the same input data.

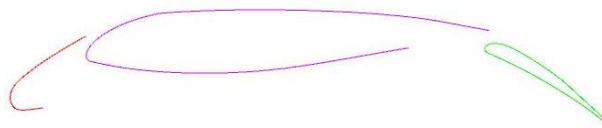
In order for *ffatrans* to function properly the boundary conditions for the geometry must be defined in such a way that each surface to be computed must belong to a single boundary. This means that for example a three-element aerofoil should have a boundary defined for each of the elements and that any part of the aerofoil (for example the cove) which is not of interest when predicting transition should belong to a different boundary. As an example the A310 high lift configuration is shown in figure 1. In

Figure 1. A310 wing showing boundary surfaces



this example the slat and main wing surfaces have been split into 2 separate boundaries with the coves being separated from the rest of the aerofoil. A total of 5 boundaries are used to define the geometry. Since the coves are not of interest in the transition prediction computation they can be removed using the *ffaicut* program. This program utilises the original `.bedg` file to produce a "cut" geometry containing only the surfaces of interest for *ffatrans*. In total 3 boundaries remain, one each for the slat, main wing and flap as shown in figure 2. This cut geometry can now be used as input to

Figure 2. A310 wing showing boundary surfaces used in *ffatrans*



ffatrans. For each iteration of *ffatrans* the RANS solution obtained from Edge must be interpolated onto the cut geometry. This can be done using the *ffauinterpol* program. The resulting cut geometry and solution files together with the input files for the boundary layer and stability solvers are defined in the *ffatrans* input file.

2.3 Running the Program

As stated previously the program is executed by typing the following at the command line:

```
>ffatrans file.ainp
```

The output from the program during execution should typically look like the following (depending on the number of profiles being computed):

```
> ffatrans ffatrans.ainp
Data written to: ffatrans.log
Mesh file is: afv2_5dsweep-cut.bedg
Solution file is: afv2_5dsweep-cut-0it.bout
EDGE File to be updated: afv2_5dsweep-0it.bedg
Nr. of partitions: 1
Cf data NOT used: ICFOPT= 0
3 profiles in total
Profile 1 side 1
  Xtr= -0.130867481      Node= 28   Delta_X= 1.29497368E-02
Profile 1 side 2
  Xtr= -0.171981692      Node= 33   Delta_X= 2.73647383E-02
Profile 2 side 1
  Xtr= 0.492208838      Node= 33   Delta_X= 0.114407592
Profile 2 side 2
  Xtr= 4.82362024E-02    Node= 127  Delta_X= 3.53321284E-02
Profile 3 side 1
  Xtr= 1.18179333      Node= 63   Delta_X= 7.28266388E-02
Profile 3 side 2
  Xtr= 0.993331254      Node= 90   Delta_X= 1.76915079E-02
Updating laminar_turbulen field in afv2_5dsweep-0it.bedg
Grid: 1
Grid: 2
Grid: 3
Writing afv2_5dsweep-0it.bedg
DONE.
```

More detailed information is written to the log file (`ffatrans.log`). The data written to standard output consists of information on the files used to run the program and which file is to be updated with the new transition information. Each side of each profile is calculated in turn and the transition location (`Xtr`), the equivalent Edge node number (`Node`) and the length of the transition region (`Delta_X`) for each side is shown. This information is used to update the original `.bedg` file on each grid level (if multigrid) and on each partition (if Edge computation is performed on multi-CPU). An ffa-formatted file called `ffatrans.bdat` is also produced. This file contains all the information on the coordinates, pressure distribution, transition locations for each profile. Additional data from the boundary layer solver and stability solver is saved in the files `pN-sI-X.<suffix>` where:

`N` is the profile number
`I` is the side of the profile
`X` is one of the following: `geo` (geo file from bl code)
`bl` (output from bl code)
`st` (output from stability code)
`env` (envelope from stability code)
`<suffix>` is either `.dat` for input data or `.out` for output data

2.4 Helpful tips

Here are some things the user should bare in mind when running `ffatrans`. Since the program updates the `.bedg` file it is recommended that the user makes a copy of this file before running the program. It is also a good idea to check that the updated `laminar_turbulen` field is satisfactory. This

can be done quite easily by firstly setting the parameter **IPOST** to an appropriate value in Edge, (e.g 4), rerunning the solver with **ITMAX** set to 0, hence producing an updated `Post.bout`. This file can then be converted for visualisation in Enight using the *uvol* program.

3 Description of the Method

The first step in the transition prediction procedure is to obtain the stagnation point on each of the aerofoil surfaces. This is done by checking each point on each surface for the maximum value of C_p . With the maximum value found the stagnation point is defined and the surfaces are split into a lower and upper side at this point. Due to the unstructured data format used in the Edge solver it is necessary to use a sorting routine to sort the points and data on each surface so that the first point is located at the stagnation point and the last point is located at the trailing edge of the surface. At this stage the user has the choice of either letting *ffatrans* detect laminar separation from the skin friction data contained in the edge solution file (**ICFOPT** = 1) or letting the boundary layer solver detect separation (**ICFOPT** = 0).

3.1 Using Cf Data to Define Transition

This method is used when **ICFOPT** = 1 is set in the input file. Skin friction data can be extracted from the RANS solution and used to find separation points on the aerofoil. Starting at the stagnation point and advancing toward the trailing edge of the aerofoil the sign of the the skin friction coefficient is monitored. If the coefficient changes sign separation has been detected. This point is used to define the point of transition. The extent of the transitional region is defined using the method outlined in section 3.4.

3.2 Using BI3D to Define Transition

This is the recommended method for predicting transition due to the increased accuracy obtained from the boundary layer analysis. It is selected by setting **ICFOPT** = 0 in the input file. In this case the sorted surface data is reformatted and input to the boundary layer solver, *BI3D*. *BI3D* solves the boundary layer equations using the infinite swept wing approximation. Once again, the stagnation point is used as the start point for the computation and the trailing edge is the last point. If separation is detected by *BI3D* the calculation is interrupted and the separation location is used as the last point. The boundary layer solution is then used as input to the stability solver. Depending on the outcome of the stability computation one of the following results is obtained:

1. Laminar separation detected by *BI3D* at point P.
2. Limiting N-factor (**NTSTRA** or **NCFTRA**) exceeded at point P.
3. Maximum N-factor lower than limiting N-factor, no laminar separation.

For case 1 the stability analysis is carried out up to the point P. If the limiting N-factor has not been exceeded before this point is reached point

P is defined as the transition location. In case 2, the surface point P is used directly as the point of transition. For case 3, there is no transition detected and the surface is considered laminar. In all three cases the laminar/transition data is exported back to Edge using the procedure outlined below. A sample input file to *BI3D* is provided in appendix B.

3.3 Database Method for Stability Analysis

The database method developed by ONERA and used here is an e^N method which is based on the relative amplification of the discrete frequency disturbance which first reaches the preset transition level of e^N (limiting N-factor in the input file to *ffatrans*). The input parameters required to run the database program are stored in the file given under **CFSTAB** in the *ffatrans* input file. A typical input file is provided in appendix C.

3.4 Exporting Transition Data Back to Edge

Instead of simply exporting a single transition "point" directly back to Edge a more sophisticated procedure is applied in which the turbulence is ramped from laminar to fully turbulent using an intermittency function, over a distance defined by a transition length model.

3.4.1 The Intermittency Function

The onset of transition is generally defined as to be where turbulent spots appear. The turbulent spots grow and merge as they travel further downstream finally resulting in a fully turbulent flow. A function can be defined which represents the intermittent appearance of the turbulent spots in the flow. The intermittency model developed by Dhawan and Narasimha [2] is implemented in the program and can be defined as:

$$\gamma = 1 - \exp[-0.411\xi^2] \quad (1)$$

Defining X as the location from the object under consideration and X_{tr} as the location of transition then ξ can be given as:

$$\xi = \frac{X - X_{tr}}{\lambda} \quad (2)$$

where λ represents the extent of the transitional region and can be defined as:

$$\lambda = \frac{X_t - X_{tr}}{3.36} \quad (3)$$

where X_t is the location where the the flow is considered to be fully turbulent and hence $\Delta X = X_t - X_{tr}$ is by definition the overall length (extent)

of the transitional region. We can now rewrite the intermittency function using the above definition as:

$$\lambda = 1 - \exp \left[-4.6 \left(\frac{X - X_{tr}}{\Delta X} \right)^2 \right] \quad (4)$$

The intermittency is therefore a function of two parameters, the location of transition and the overall length of the transitional region.

3.4.2 The Transition Length Model

The overall length of the transitional region (ΔX) has been investigated by among others Narasimha [5], Chen and Tyson [1] and Walker [7] for flow over a flat plate. Here Walker's formulation has been used which is defined as:

$$Re_{\Delta X} = 5.2 Re_{X_{tr}}^{1/2} \quad (5)$$

and relates the Reynolds number over the transitional region to the Reynolds number at the location of transition. Using this relationship and knowing the location of the transition point from the stability analysis the overall length of the transitional region can be defined as

$$X_t = 5.2 \cdot X_{tr}^{3/4} \cdot \left(\frac{\nu}{U_e} \right)^{1/4} \quad (6)$$

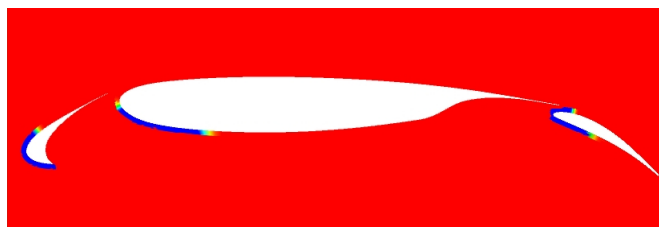
where $\nu = \mu/\rho$ is the kinematic viscosity and U_e is the tangential velocity at the boundary layer edge. Now that the length of the transition region is known this information can be firstly exported to the cut geometry where the points on each surface are flagged as laminar, turbulent, or transitional where the transitional values are obtained from the intermittency function. The flagged values of the points on the cut geometry are now used to set the value in the whole computational domain. Within a normal distance to the closest wall, defined by **MAXWAD**, the point in the domain is given the flagged value of the closest wall point. This information is then used to limit the turbulence production in the RANS computation.

4 Examples

4.1 Three Element Aerofoil

In figure 3 an example of the predicted transition locations on a 3 element high lift configuration is shown. In this figure the red region denotes areas where the flow is fully turbulent. The blue regions on and close to each of the profiles denote areas which are laminar. The transition region is denoted by the range of colours between red and blue. This figure is produced by plotting the `laminar_turbulen` dataset from the post-processed edge solution file in Ensign. The extent of the laminar and transition regions in the normal direction is controlled by the `MAXWAD` parameter in the input file.

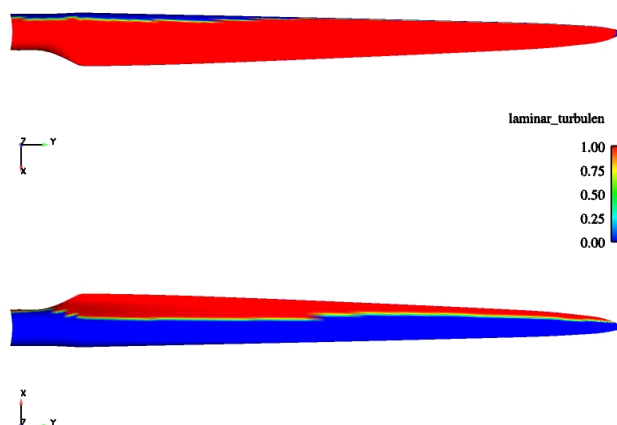
Figure 3. Laminar and turbulent field for a multi element configuration



4.2 Wind Turbine Blade

In this example `ffatrans` has been applied to predict transition on a rotating wind turbine blade. A total of 33 radial sections were computed. The image below shows the laminar, transition and turbulent regions on the suction (upper) and pressure (lower) side of the blade.

Figure 4. Laminar and turbulent field on a wind turbine blade



5 Further Development

Some improvements to the program need to be made before it can be applied to general geometries. The most important modification is the sorting routine which reorganises the unstructured data from the `.bedg` file, see `bcpext.f`. At present this is done in a somewhat ad-hoc manner where the user is required to input a set of coordinates for each profile. This method was developed by Adam Jirasek. It works well for single element aerofoils at low angles of attack but can be difficult to use for multi-element aerofoils with large flap and slat deflections. A method developed by Ardeshir Hanifi is more promising and should replace the old sorting routine.

Integration of a more advanced stability program should also be prioritised. At present only the database method is available. A logical step would be to include the NOLOT solver.

6 The Source Code

The complete source code for *ffatrans* should be available as part of the Edge source under the `programs` sub-directory and should include the following:

<code>Makefile</code>	The Makefile for <i>ffatrans</i>
<code>ffatrans_main.f</code>	The main routine
<code>bcpext.f</code>	Extracts C_p on each surface from Edge solution, splits surface into upper and lower and sorts data using point of maximum C_p
<code>bcpcfext.f</code>	As above but also extracts C_f
<code>ctrfnc.f</code>	Computes intermittency and transition length for ICFOPT = 1
<code>cxbl3d.f</code>	Controls boundary layer and stability computations and computes transition data
<code>dtrset.f</code>	Exports the transition information back to the <code>.bedg</code> file

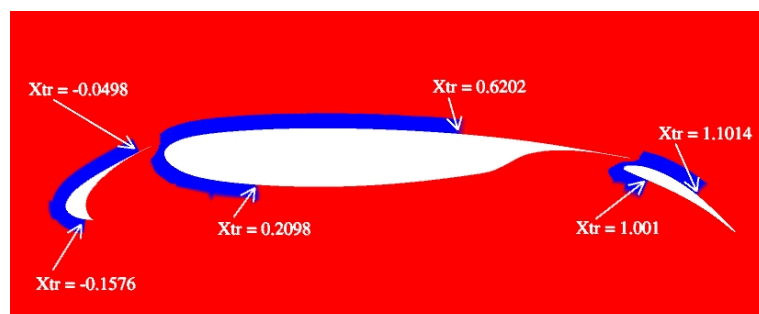
7 ffaspectran

If the user is interested in applying transition at a predefined point on a 2D geometry then this can be done using the *ffaspectran* program. The location of transition is defined in this case at a specified coordinate location for each side of the aerofoil geometry. Only the coordinate in the flow direction is required. The geometry is split into an upper and lower side at the leading edge of the aerofoil. Transition occurs at the point on the aerofoil surface which is closest to the point given in the input file. An example is given in figure 5. The input parameter **ITRCO** defines the transition locations as shown below in an extract from the input file.

```
*
*   GIVE THE TRANSITION COORDS ON EACH PROFILE
*   lower side, upper side
*
ITRCO,R,3,2,0
-0.16 -0.05
0.2 0.6
1.0 1.1
*
```

Note that the actual transition locations differ slightly from those defined in the input file. This is also seen in the output from the program where x_{tr} is the point of transition. The thickness of the laminar region is exaggerated for visualisation purposes and can be controlled using the **MAXWAD** parameter.

Figure 5. Specifying transition with *ffaspectran*. Transition located at x_{tr}



```
[cys@mustang test-transdefine]$ ffaspectran ffaspectran.ainp
Cut bedg file is: afv2d-extend-cut.bedg
Edge File to be updated: afv2_5d-extend.bedg
Nr. of partitions: 1
Profile 1 side 1
  Xtr= -0.157619730      Node= 21
Profile 1 side 2
  Xtr= -4.98019047E-02  Node= 47
Profile 2 side 1
  Xtr= 0.209757552     Node= 97
Profile 2 side 2
  Xtr= 0.620172441     Node= 99
Profile 3 side 1
  Xtr= 1.00161362      Node= 37
Profile 3 side 2
  Xtr= 1.10142422      Node= 107
Updating laminar_turbulen field in afv2_5d-extend.bedg
Grid: 1
Grid: 2
Grid: 3
Writing afv2_5d-extend.bedg
DONE.
```

The source code for *ffaspectran* can be found in the `programs` subdirectory of the Edge source.

References

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- [6] Stock, H.W. & Haase W. A Feasibility Study of e^N Transition Prediction in Navier-Stokes Methods for Airfoils. *AIAA Journal*, Vol. 37, Nr. 10, 1999.
- [7] Walker, G.J. Transitional Flow on Axial Turbomachine Blading. *AIAA Journal*, Vol. 27, Nr. 5, 1989.

Appendix A

Sample ffatrans input file

```
DEFAULT, L, 1, 0, 18
*****
*
*                               VERSION  1.0
*
*****
*  DEFAULT SETUP FOR FFATRANS
*
*****
*  NAME OF BOUNDARY LAYER CODE INPUT FILE
*
CFBL3D,L,1,1,0
'bl3D.in'
*
*  PATH TO THE BOUNDARY LAYER CODE EXE
*
CFBLEX,L,1,1,0
'~/bin/i686/bl3D'
*
*  CFIEDG IS THE EDGE FILE TO BE USED
*
CFIEDG,L,1,1,0
'dev_ffatrans.bedg'
*
*  CFIMSH IS THE MESH FILE PRODUCED FROM ffaucut
*
CFIMSH,L,1,1,0
'ffatrans-cut.bedg'
*
*  CFIPOS IS THE POSTPROCESSED SOLUTION PRODUCED FROM ffaufinterp
*
CFIPOS,L,1,1,0
'Post-cut.bout'
*
*  CFISOL IS THE SOLUTION FILE PRODUCED FROM ffaufinterp
*
CFISOL,L,1,1,0
'ffatrans-cut.bout'
*
*  NAME OF STABILITY CODE INPUT FILE
*
CFSTAB,L,1,1,0
'parab.inp'
*
*  PATH TO THE STABILITY CODE EXE
*
CFSTEX,L,1,1,0
'~/bin/parabola'
*
*  SHOULD Cf DATA BE USED =1 OR NOT =0
*
ICFOPT,I,1,1,0
0
*
*  GIVE THE DIRECTION OF THE CUT PLANE:
*  ICUT  = 1 2 (X,Y)
*         = 1 3 (X,Z)
*         = 2 3 (Y,Z)
ICUT,I,1,2,0
1 2
```

```
*
*   CONSTANT USED IN TRANSITION LENGTH MODEL
*   ITLMC = 1, WALKERS ORIGINAL MODEL Re = 5.2...
*           = 2, WALKERS MODIFIED MODEL Re = 10.4 ...
*
ITLMC,I,1,1,0
1
*
*
*   MAXIMUM DISTANCE OF ALL LAMINAR REGIONS, BEYOND IT IS TURBULENT
*
MAXWAD,R,1,1,0
0.03
*
*   CROSS-FLOW (2.5D) TRANSITION N FACTOR
*
NCFTRA,R,1,1,0
7.
*
*   T.S (2D) TRANSITION N FACTOR
*
NTSTRA,R,1,1,0
7.
*
*   MIN T.S N FACTOR
*
NTSMIN,R,1,1,0
0.0
*
*   SWEEP ANGLE FOR 2.5D CALCULATIONS
*
SWEEP,R,1,1,0
40.0
*
*   OMEGA, IF ROTATING (rad/s)
*
OMEGA,R,1,1,0
0.
*
*   NUMBER OF PARTITIONS
*
NPART,I,1,1,0
1
```


Appendix B

Sample BI3D input file

A sample input file is shown below. A total of 17 parameters are required. A short description of each input parameter is also provided.

```
150          !number of points in normal direction
10          !etamax
1          !mutask(1:sutherland, 2:polynomial)
1          !kptask(1:keye, 2:polynomial)
1          !prtask(1:constant, 2:variable Prandtl nr.
1          !cptask(1:constant, 2:variable cp)
.72        !prandtl number: (0 to be computed)
1.40 287.0 !gamma and gas constant
250        !index of last station
0 2 250 1  !ftype, ifirst, ilast , istep
0          !nr of new points in each interval
1          !order of interpolation
0          !isim
```


Appendix C

Sample Database input file

The input file to the database solver (parabola) consists of 7 parameters. The file itself is a plain text file. In the example below an explanation of each input parameter is provided. These are not required in the actual input file.

```
15000 ! maximum frequence (Hz)
50    ! number of different frequencies
160   ! maximum number of stations in x
0     ! coordinate syst 0 : (X,Z), 1 : (xi,eta)
0     ! icomp : 1 = incompressible
88.5  ! psimax-CF (degre)
1     ! data format 1=eurotrans version 1
      2=eurotrans/hylda
      3=elfin
      5=Castet
```


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Sammanfattning <i>ffatrans</i> predicts regions of transition on 2D and 2.5D aerofoil sections using boundary layer and stability analysis. It uses RANS solutions from the Edge solver as a start point. Transition is ramped over a distance computed using a transition length model. An intermittency function is used to model the growth of turbulence.		
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