TCGRID 3-D Grid Generator for Turbomachinery User's Manual and Documentation

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Introduction

TCGRID (Turbomachinery C-GRID) is a three-dimensional grid generation code for turbomachinery blades. The code can generate single or multiblock grids that are compatible with various analysis codes including SWIFT and ADPAC. Single- block grids can be either C-type or H-type, and can be for linear cascades or annular blade rows. Multi-block grids must use a C-type grid around the blade, and can add an H-grid in the inlet region and O-grids in the hub or tip clearance regions.

A brief description of TCGRID and an example of a compressor grid are given in [1]. Examples of turbine grids generated with TCGRID can be found in [2]. "*Test Cases Included with TCGRID*" on pp. 3 shows examples of grids for turbines, axial compressors, and centrifugal impellers that have been generated with TCGRID.

All geometry manipulation in TCGRID is done using parametric splines, so the code can handle axial, mixed, and centrifugal flow machines. Monotone splines added in version 400 follow slope discontinuities without overshoots. The input blade geometry can be translated, rescaled, and flipped tangentially, and full control of spacing along the blade surface is provided. Blade-to-blade grids are generated using an efficient elliptic solver that gives control of spacing and angles at the blade and outer periodic boundary. Grids are reclustered spanwise with control over spacing at the hub, casing, and clearance regions.

TCGRID is written completely in Fortran 90 and runs as a quick batch job on Linux, Mac, or Windows computers. Code input is supplied in a text file with grid parameters specified using convenient namelist input. Hub and casing geometries are specified as coordinate pairs. Blade shapes may be specified in MERIDL format, Crouse-Tweedt design code format, or specified directly by the user as coordinate triplets. Some printed output is provided. No graphical output is provided, but grid files can be read directly and plotted using the public domain CFD visualization code PLOT3D, or the commercial codes FieldView, TecPlot, and EnSight CFD.

This documentation briefly describes how the TCGRID code works. Instructions for dimensioning, compiling, and running TCGRID are given for Linux systems, but the process should be similar for Mac or Windows systems. The namelist input variables and the hub, tip, and blade input are described in detail. Finally, an outline of the code structure given and the output file format is described.

Features of TCGRID

Applications
Linear cascades
Axial compressors and turbines
Isolated blade rows or multistage machines
Centrifugal impellers and mixed-flow machines without splitters
Radial diffusers
Pumps

Grid Types
C- or H-grids around blades
C-grid with upstream H-grid
O-grids in hub- and tip-clearance regions
Curved inlet and exit boundaries for closely coupled blade rows
Multistage machines can be modeled by merging C-grids for individual blades using a utility called MULTIX.

Formulation
Blade-to-blade grids generated with a fast elliptic solver (GRAPE)
Spanwise reclustering done using monotone cubic splines
H-grids in inlet regions and O-grids in clearance gaps generated algebraically

Input
Namelist input of grid parameters
Hub and casing geometries input in (z, r) coordinates
Blade geometries input in general (z, r, θ) coordinates, or MERIDL format (z, r, θ–upper, θ–lower) or (z, r, $\Delta\theta$)

Printed Output
Input parameters
Convergence information for blade-to-blade grids
Spanwise output of inlet, leading edge, trailing edge, and exit coordinates
Index file with grid size information for SWIFT or other CFD codes

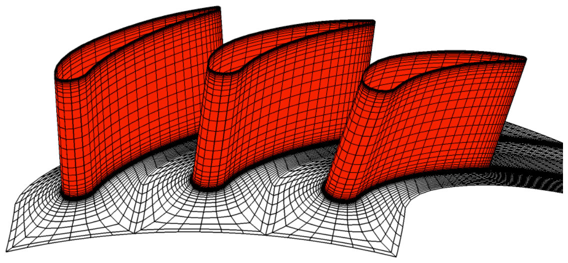
Grid & Debug Output
Grid files are written as binary data in standard PLOT3D format
Intermediate grid files can be output for debug purposes. Debug files include reclustered blade coordinates, the 2-D throughflow grid, and 2-D blade-to-blade grids that may be useful for other purposes.

Computer Requirements
Fortran 90 compatible compiler
Runs as a quick batch process on Linux, Mac, or Windows computers

Graphical Output
No graphical output is provided with TCGRID, but access to some CFD visualization package is absolutely necessary to view and evaluate new grids. Grid files are in standard PLOT3D format and can be read directly and plotted with the public-domain CFD visualization tool PLOT3D or the commercial tools FieldView, TecPlot, or EnSight CFD. Check the following web sites for more information.

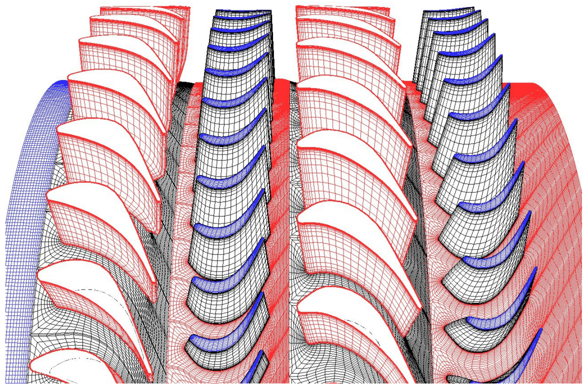
PLOT3D :	http://www.nas.nasa.gov/Research/Software/swdescription.html
TecPlot:	http://www.tecplot.com/
FieldView:	http://www.ilight.com/
EnSight CFD:	http://www.ensightcfd.com/

Test Cases Included with TCGRID



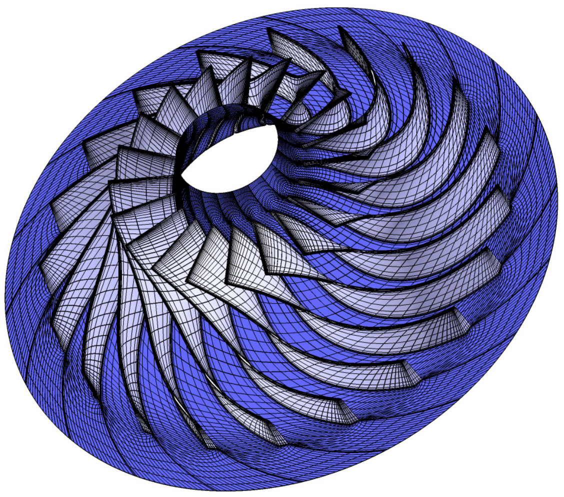
Goldman annular turbine vane

- A simple extruded vane with constant-radius endwalls
- 1-block grid



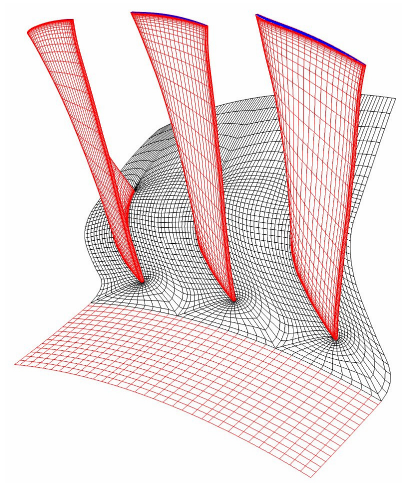
Space Shuttle Main Engine (SSME) fuel turbine

- 2-stage high-pressure turbine
- 7-block grid with clearances over the rotors
- Individual grids are run separately and assembled with multix



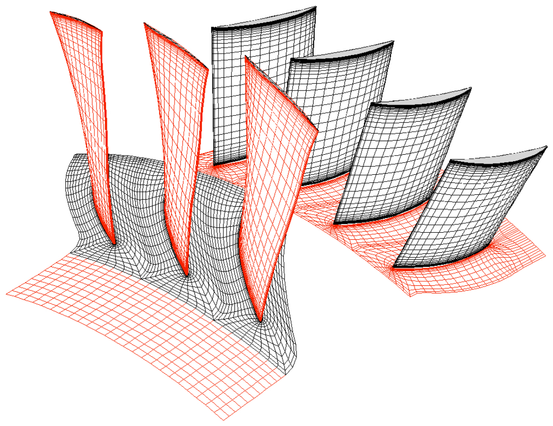
Large, Low-Speed Centrifugal Impeller

- 5 ft. diameter backswept research impeller
- Single-block H-grid



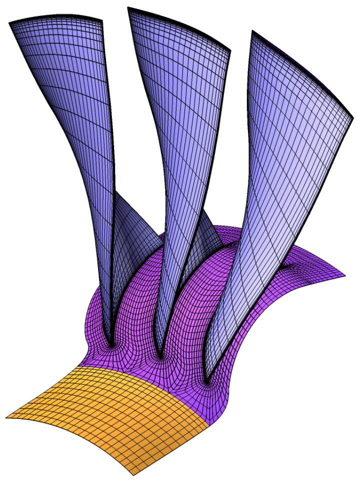
Rotor 37

- Transonic inlet rotor for a core compressor
- 3-block grid with tip clearance



Stage 35

- Transonic inlet stage for a core compressor
- 3-block rotor grid with tip clearance
- 2-block stator grid with hub clearance
- Individual grids are run separately and assembled with multix



Rotor 67

- Low aspect ratio transonic fan
- 3-block grid with tip clearance

Unzipping, Compiling, and Running TCGRID

The following documentation is for a Linux system. The general process should be the same on a Mac or PC, but you may need to change details.

TCGRID is supplied as a zip file. It will unzip into a directory with the same name as the file. This documentation should be in the main directory. There are subdirectories for source code and test cases. To unzip:

```
   unzip tcgrid_305.zip
```

Compiling

Go to the src directory and edit the Makefile. Compiler commands are set for the Intel Linux compiler,

```
   FC = ifort –O2
```

Change the commands as necessary for your compiler. Moderate optimization usually works well. Near the bottom of the Makefile there may be a line that moves the executable to a bin directory. Keep or remove this line as desired.

```
   mv tcgrid ~/bin
```

Save the file and exit.

Edit modules.f90 and change the maximum array size if desired. All large arrays are dynamically allocated, but some small working arrays are statically dimensioned using parameters ni, nj, and nk. Modifying these parameters will not substantially change the memory required by TCGRID.

```
   module param
   !  maximum dimensions of any grid, used for work arays
      integer,parameter::ni=321, nj=161, nk=95, nb=2*ni
   end module param
```

Save the file and exit.

Run make. Move the executable to a directory in your path.
Clean up object and executable files if desired by running

```
   make clean
```

Running TCGRID

TCGRID is run as a standard Linux process:

```
   tcgrid < input_file > output_file
```

The output file is not too useful so you may want to ignore the "> output_file", and just let the output scroll up the screen. The last page of output does print coordinates of the inlet boundary, blade leading and trailing edges, and exit boundary, which can be useful.

Output Files

The output grid file is written to Fortran unit 1 (fort.1). A SWIFT index file is also written to fort.10. The index file is in ASCII format and can be edited as desired. Debug grid files may be written to fort.11 - fort.19, depending on *idbg* flags set in the input file. All grid files are written as unformatted binary files. They can be used immediately by SWIFT, and can be read into CFD visualization codes using the unformatted PLOT3D option. Output files should be renamed after running TCGRID,

```
      mv fort.1  case_name.xyz
      mv fort.10 case_name.ind
```

Default File Names

Setting *iopen=1* in the namelist input causes all files to be opened explicitly with a default file name. For example, the grid will be named grid.xyz. Other file names are given with the *iopen* options under " *&nam3* - Algorithm Parameters" on page 12. By using the default file names you can avoid the file renaming steps, but you may want to rename the files with more descriptive names later.

TCGRID Input – Overview

TCGRID input consists of five blocks of namelist input (&nam1 - &nam5), followed by a title, then hub, tip, and blade coordinates. All grids require the title, hub, tip, and blade coordinate input, (see *Hub, Tip, and Blade Input, page 16*). Many of the namelist variables are initialized in modules.f90. Required input variables that are not initialized are listed below, followed by some comments regarding optional variables. All variables are described in detail in the section entitled *Namelist Input*.

C-grids

To generate the main C-grid around the blade set the following variables:

&nam1 - im, jm, km, merid, itl, icap.

- To change clustering along the blade surface, along the span, and upstream and downstream of the blade, use *iclus*, *icluss*, and *iclusw*, respectively.
- Use *iclus2d*=1 to cluster the meridional grid using the same spanwise clustering as the input blade. For simple, ruled blades use *iclus2d*=0.
- For complex flow paths increase the meridional grid size using *i2d* and *k2d*.

&nam2 - *nle, nte, dsle, dste, dswte, dswex, dsmin, dsmax, dshub, dstip*.

- Vary the leading- and trailing edge radii with span using *dsthr*.
- Move the location of the leading edge clustering using *dsra*.

&nam3 - *iterm*.

- For a quick check of a new grid, set *iterm*=0. Use PLOT3D to check leading- and trailing edge spacings, surface clusterings, boundary locations, and outer boundary spacings.
- If something goes wrong, use the array *idbg*(9) to generate debug grids to check input coordinates or intermediate grids (see *Debug Output Files* on page 22.)
- Use *aabb* and *ccdd* to move points towards or away from the blade and outer boundary respectively.

&nam4 - Inlet and exit boundary coordinates *zbc* and *rbc* are required.

&nam5 - Most variables can defaulted.

- Use *zscale*, *tscale*, *rscale*, *ztrans*, and *tflip* to manipulate the input blade coordinates.
- Use *ioble*, *exl*, and *exr* to change the outer boundary shape.
- Use *iwakex* and *jwakex* to stretch the wake grid.
- Set *iswift* = 1 to generate grids for SWIFT.

H-grids for Blades

Most of the parameters required for C-grids are also required for H-grids. In addition, the following indices must be set:

&nam1 - *igch*=1, *ilh, itl*.

&nam2 - Spacing parameters are interpreted as follows:

- *dsin* = spacing at inlet,
- *dsle* = spacing at leading edge,
- *dste* = spacing at trailing edge,
- *dswex* = spacing at exit
- *dsmax* is reset to *dsmin* internally.

&nam3 - Some algorithm control parameters are reset for consistency.

- *ccdd* is reset to *aabb*.
- *omegpq* is reset to *omegrs*.

Linear Cascades

To generate a grid for a linear cascade set the following:

&nam1 - *igeom* = 1,

&nam2 - *gap*.

Inlet H-grid

To generate an inlet H-grid, set the following:

&nam1 - *igin* = 1, *imi*.

&nam2 - dsin.

- Since the inlet H-grid is generated algebraically from the blade C-grid, the C-grid must converge for the H-grid to work correctly.

Tip Clearance O-grid

To generate a tip clearance grid, set the following:

&nam1 - *igclt* = 1, *jmt, km*t.

&nam2 - *cltip*, *dsclt*.

- The number of points in the i-direction depends on the C-grid size. Since the clearance O-grid is generated algebraically from the surrounding C-grid, the C-grid must converge for the O-grid to work correctly.

Hub Clearance O-grid

To generate a hub clearance grid, set the following:

&nam1 - *igclh* = 1, *jmh, kmh*.

&nam2 - *clhub*, *dsclh*.

- The number of points in the i-direction depends on the C-grid size. Since the clearance O-grid is generated algebraically from the surrounding C-grid, the C-grid must converge for the O-grid to work correctly.

Multistage Grids – Grid requirements

Multistage C-grids are generated one blade row at a time, and then are merged using a Fortran program called multix.f. The individual grids must meet certain requirements:

1. Use identical hub and tip coordinates for all blade rows.
2. The blades must be in the correct location and orientation. Use *ztrans* to move the blades axially, and *tflip* to flip the θ- coordinates if necessary.
3. The grids must match at an interface between the blades. Set the exit boundary coordinates of grid 1 to the inlet boundary coordinates of grid 2. Place the interface midway between the blades, or close enough to blade 2 to get a good C-grid.
4. For SWIFT, the grids must overlap exactly one cell at the interface. On grid 1 set *dswex* to give a fine spacing near the exit, and set *dslap = dswex*. This resets the grid spacing at the exit from approximately *dswex* to exactly *dslap*. On grid 2 set $dsmax_2 = dslap_1$. This will cause the dummy grid line from grid 2 to overlap grid 1 by *dsmax*. (Not necessary for ADPAC.)
5. The relative circumferential spacing between the grids does not matter.
6. SWIFT version 400 now allows non-point-matched grids at mixing planes. Neighboring grids can have differennt numbers of points and discontinuous spacings in the spanwise direction. However, using

continuous grids across mixing planes may improve solution continuity, and will simplify printed and graphical output at a given spanwise location.

Multistage Grids – Multix Utility and Makgrid.csh Script

Multix.f merges two PLOT3D files and two index files without much checking. The steps are as follows:

1. Compile multix.f and make sure the executable is in your path.
2. Run TCGRID for grid 1. Rename fort.1 to name1.xyz. Rename fort.10 to name1.ind.
3. Run TCGRID for grid 2. Rename fort.1 to name2.xyz. Rename fort.10 to name2.ind.
4. Run multix. It will prompt for name1 and name2.
5. The output files are named out.xyz and out.ind. Rename them as desired
6. Repeat steps 1–5 to add more files if necessary.
7. The index file out.ind will have the correct format and grid sizes, but you will have to edit it and change connectivity, boundary condition flags, etc. as described in the SWIFT documentation.

Multistage test cases include a c-shell script called makegrid.csh that generates the complete multistage grid for that case.

Namelist Input

Defaults are given in angle brackets, <default=value> or <default.> If no default is given the value MUST be input. Relevant figures are given in parentheses (Fig. #.)

***&nam1* - Grid Size Parameters**

Many grid size parameters are illustrated in Figs. 1, 2, and 4.

merid	Flag for type of blade input. See *Hub, Tip, and Blade Input* on page 16, and Figs. 5 and 6 for complete descriptions of the blade input formats.
	= 0 Blade input in stacked sections, (z, r, θ). Completely general, (Fig. 5). <default>.
	= 1 Blade input in Crouse/Tweedt design code format, (z, r, θ) (Fig. 5). Like *merid*=0 but ordered differently.
	= 2 Blade input in MERIDL format, (z, r, θ-upper, θ-lower), (Fig. 6).
	= 3 Blade input in MERIDL format, (z, r, θ, Δθ), (Fig. 6).
im	Grid size in i- (streamwise) direction, (Figs. 1, 2).
jm	Grid size in j- (blade-to-blade) direction, (Figs. 1, 2).
km	Grid size in k- (spanwise) direction, (Fig. 4).
itl	C-grid: i-index of lower trailing edge point, (Fig. 1).
	H-grid: number of cells downstream of the trailing edge, (Fig. 2).
icap	Number of cells on the inlet part of the C-grid, equally-spaced. Remaining cells are distributed over the periodic boundaries. Increase *icap* to pull points towards inlet, and vice-versa, (Fig. 1).
igeom	Flag that tells whether grid will be for a linear cascade or an annular blade row.
	= 0 Annular blade row <default>.
	= 1 Linear cascade.
iclus	Flag for type of clustering along the blade surfaces.
	= 1 Hyperbolic tangent clustering - smoothest, but may be sparse at blade center if *im* is too small <default>.
	= 2 Hermite polynomial clustering - more uniform, but may grow too quickly near leading and trailing edges. Good for large *im*.
icluss	Same as *iclus*, but for clustering in the spanwise direction.
iclusw	Same as *iclus*, but for streamwise clustering downstream in the wake, and also upstream for an H-grid.
iclus2d	Flag that sets spanwise clustering of the meridional grid on which the blade-to-blade grids are generated.
	= 0 Meridional grid is equally spaced between hub to tip. Good for ruled blades.

	= 1 Meridional grid has approximately the same spanwise clustering as the input blade sections. Use this option if the input blade sections are spaced non-uniformly along the span to resolve twist or fillets. <default>.
iclusmt	Flag for clustering scheme used to generate the meridional grid. If the default fails (set idbg(3) = 1 and plot the meridional grid written to fort.13,) then try *iclusmt = 0*.
	= 0 Original clustering scheme distributes points on the hub and tip equally with arc length. Can fail for unusual flow paths.
	= 1 Distributes points on the hub, then searches for the nearest point on the tip. Usually produces a nearly orthogonal grid, but can fail for steps in the casing <default>.
i2d	Number of i- (streamwise) points on the coarse meridional grid used to define the passage. Typically 21 for an axial machine, 41 or more for a centrifugal. <default = 21, max=101>.
k2d	Number of k- (spanwise) points on the coarse meridional grid used to define the passage. Should be roughly equal to the number of input blade sections *nbs*. <default = 11, max=50>.

Parameters for H-grids Around Blades

igch	Flag to set C- or H-grids around blade
	= 0 C-grid <default>.
	= 1 H-grid.
ilh	H-grid: number of cells upstream of the leading edge, (Fig. 2).
itl	H-grid: number of cells downstream of the trailing edge, (Fig. 2).

Parameters for Inlet H-grids

igin	Flag to generate an inlet H-grid ahead of the main C-grid. Not used if *igch* = 1.
	= 0 No inlet H-grid <default>.
	= 1 Generate inlet H-grid.
imi	Number of i- (streamwise) points in the inlet H-grid. Only used if *igin* = 1.

Parameters for Clearance Gap O-grids

igclh, igclt	Flag to generate hub or tip clearance O-grids.
	= 0 No clearance O-grid <default>.
	= 1 Generate clearance O-grid.
jmh, jmt	Number of j- (radial) points in the hub or tip clearance grid, (Fig. 4). Only used if *igclh* = 1 or *igclt* = 1.
kmh, kmt	Number of k- (spanwise) points in the hub or tip clearance grid, (Fig. 4). Only used if *igclh* = 1 or *igclt* = 1.

&nam2 **- Grid Spacing Parameters**

All spacing parameters must be input in the units desired for the final grid. All spacing parameters named "*ds*…" refer to spacing along some arc length, and not in a particular coordinate direction. Values suggested as "e.g." should give a good initial guess but may need to be modified after examining the initial grid.

nle	Number of points equally-spaced around the blade leading edge, typically 15.
nte	Number of points equally-spaced around the blade trailing edge, typically 10.
dsle	Spacing around the leading edge at the hub, e.g. $\pi \cdot rle / nle$.
dste	Spacing around the trailing edge at the hub, e.g. $\pi \cdot rte / nte$.
dsthr	"ds tip-to-hub ratio." *Dsle*, *dste*, and *dswte* are taken as hub values and are varied linearly with span to this factor at the tip. Allows the leading edge radius, etc. to increase or decrease (usually decrease) with span. <default = 1>.
dswte	"ds wake trailing edge." Spacing away from the trailing edge on the wake cut of C-grid (Fig. 1) or periodic boundary of an H-grid (Fig. 2). Should be $\approx dste$.
dswex	"ds wake exit." Spacing at exit of the grid. Should be 5-10 percent of the distance between the trailing edge and the exit. (Figs. 1, 2).
dsmin	Wall spacing at the blade. Typically chord/10,000 for viscous grids, (Figs. 1, 2). Note: SWIFT's blade surface output gives y+, the grid spacing at the wall in turbulent wall units. y+ should be $O(1-5)$. If y+ is too large, you may need to rerun your grid with *dsmin*, *dshub*, and *dstip* reduced accordingly.
dsmax	Spacing away from the periodic boundary, e.g. (midspan pitch)/*jm*, (Figs. 1, 2).
dsin	Spacing away from the inlet of inlet H-grid, (Figs. 1, 2). Only used if *igin* = 1 or *igch* = 1.
dsra	"ds ratio." (Pressure surface arc length)/(total surface arc length). Used to locate the center of the leading edge clustering on the blade. The clustering is centered about *dsra* × (total surface arc length.) Typical values are 0.5 for symmetrical blades, about 0.49 for compressor blades, and about 0.45 for highly-cambered turbine blades. Only used for general blade input, *merid* = 0. = 0 TCGRID assumes that there are the same number of blade input coordinates on each surface and clusters about the median input point <default>.
gap	Blade row pitch for a linear cascade. Only used if *igeom* = 1. If *igeom* = 0 the pitch is set by *nblade*. <default = 1>.
rcorn	Radius for the front corner of the C-grid, (Fig. 1.) Usually 0., but the inlet grid may be smoother with rounded corners. <default = 0.0. Ignored if *igin* = 1>.

Spanwise Clustering Parameters

The spanwise grid is clustered in 1 to 3 regions as shown in Fig. 4. The stretching function in each region is set by *icluss*. A central region is always used between the hub and casing, with wall spacings *dshub* and *dstip*. If *clhub* > 0 or *cltip* > 0, hub or tip clustering regions are added that use the following clustering parameters:

dshub, dstip	Spanwise spacing at the hub or tip, e.g. span/10,000 for viscous grid. (Fig. 4).
clhub, cltip	Hub or tip clearance height, (Fig. 4). Always needed if clearance O-grids are generated (*igclh = 1* or *igclt* = 1,) but may also be used to control clustering near the endwalls, possibly for a simple periodicity clearance model.

	= 0 No hub or tip region clustering. <default>.
	> 0 Grid is clustered near the hub or tip.
dsclh, dsclt	Spanwise spacing at the blade/clearance interface, (Fig. 4). Only used if *clhub* > 0 or *cltip* > 0. <default = *dshub* or *dstip*.>

Parameters for Blunt Trailing Edges

TCGRID can wrap grids around blades with blunt trailing edges like the blades shown in Fig. 7. Blade coordinates may be input in one of two ways depending on the value of *merid*.

merid	= 0 or 1 (general coordinate input) <default>. Blades must be input with an open trailing edge (Fig. 7a,) and *nbase* points are added automatically.
	= 2 or 3 (MERIDL input.) Blades are always input with an open trailing edge (Fig. 6,) and then:
	if *nbase* = 0 a round trailing edge is added <default>.
	if *nbase* > 0 a blunt trailing edge is assumed.
nbase	Number of intervals on the blunt trailing edge (Fig. 7a).
ibase	Flag controlling the location of the wake cut line with respect to the base of the blade (Fig. 7a). To minimize grid distortion, choose *ibase* such that the cut leaves the corner with the acute angle. If the base is symmetric (Figs. 7c or 7d) use *ibase* = 0.
	= +1 Cut line leaves the upper corner of the base.
	= 0 Cut line leaves the center of the base <default>.
	= -1 Cut line leaves the lower corner of the base.
ibevel	Flag for beveling the corner(s) of the base to reduce grid distortion (Fig. 7c). If *ibase* = 0 both corners are beveled. If *ibase* = ±1 the corner opposite the wake cut is beveled.
	= 0 No bevel <default>.
	= 1 Corner(s) are beveled.

&nam3 **-Algorithm Parameters**

See Sorenson's GRAPE code documentation [5] for more information on algorithm parameters. Most values can be defaulted.

iterm	Number of iterations for elliptic solver, usually 50 – 150. Use *iterm* = 0 to check initial grid spacings, boundary locations, etc. <default=100>.
idbg(9)	Integer flag array with nine elements for writing intermediate debug grids to Fortran units 11 – 19. Useful for debug, graphics, and possibly for grid generation in itself. For more information see Table 1 on page 22. <default = 0 0 0 0 0 0 0 0 0>.
omega	Relaxation factor for the elliptic solver, rarely changed. Acceptable values from 0.0 to 2.0 <default = 1.4>.
omegpq	Relaxation factor for the inner boundary forcing functions, rarely changed. Acceptable values from 0.0 to 2.0 Set to 0.0 for a Laplacian inner boundary. <default = 0.1>.
omegrs	Like *omegpq*, but for the outer boundary.

aabb	Exponent controlling the distance that angles and spacings at the inner boundary propagate into the interior. Small *aabb* give large distances but slow convergence, and vice versa. Any value > 0.0 is acceptable. <default = 0.45>. Set *aabb = 0.35* to cluster more points near the wall, or *aabb = 0.55 – 0.65* to reduce the clustering.
ccdd	Like *aabb*, but for the outer boundary.
csmoo	Smoothing coefficient for the periodic boundary. If *csmoo > 0.0*, a 4th-difference smoothing operator is applied to the periodic boundary. This allows the boundary points to float a little, which may reduce distortion. Not usually needed, but worth a try if the periodic boundary looks bad. Acceptable values from 0.0 to 1.0, typically 0.5. <default=0>.
iopen	Flag for opening output files explicitly by name.

= 0 Output files are written to Fortran units without explicitly opening them. <default>.

= 1 Output files are opened by name:

grid.xyz	= main grid file (binary)
index.dat	= SWIFT index file (text)
debug*nn*.xyz	= debug grid files. *nn* = 11 – 19 refer to the Fortran unit number in Table 1 on page 22.

<u>&nam4 - Boundary Coordinates</u>

zbc(3,2) and *rbc*(3,2)

Arrays of (z, r) coordinates that define three line segments used as boundaries for the upstream H-grid inlet, the blade grid inlet, and the blade grid exit, as shown in Fig. 3. The line segments are intersected with the hub and tip geometry internally, so the coordinates need not lie exactly on the hub and tip. The first index indicates the segment and the second index indicates hub or tip. The six points must be entered in the order shown below. The coordinates of the upstream H-grid inlet may be set to zero if *igin* = 0, or for a general H-grid (igch = 1).

```
zbc = z-H-hub-in,   z-hub-in,  z-hub-ex,  z-H-tip-in,   z-tip-in,   z-tip-ex
rbc = r-H-hub-in,   r-hub-in,  r-hub-ex,  r-H-tip-in,   r-tip-in,   r-tip-ex
```

The inlet and exit of the blade grid can also be specified as curves, for example at a mixing plane between closely-coupled blade rows. Boundary data is input as two or more (z,r) coordinate pairs. The data is spline fit spanwise and does not need to match the hub and tip. 3 – 4 points are usually sufficient.

inbndry	Number of points on the inlet boundary, must be ≥ 2. <Default = 0, *zin* and *rin* are ignored>.
exbndry	Number of points on the exit boundary, must be ≥ 2. <Default = 0, *zex* and *rex* are ignored>.
zin(:)	Array of z-coordinates on the inlet boundary, *inbndry* points from hub to tip.
rin(:)	Array of r-coordinates on the inlet boundary, *inbndry* points from hub to tip.
zex(:)	Array of z-coordinates on the exit boundary, *exbndry* points from hub to tip.
rex(:)	Array of r-coordinates on the exit boundary, *exbndry* points from hub to tip.

&nam5 **- Miscellaneous Parameters**

Most of these parameters can be defaulted.

iswift	Flag to set grid file for general, SWIFT, or ADPAC format.
	= 0 General grids with no dummy grid lines. Use this option for use with other flow solvers <default>.
	= 1 SWIFT code output – one or more blocks with dummy grid lines in the j-direction.
	= 2 ADPAC code output – one or more blocks, no dummy grid lines. Note: For ADPAC the j- and k-directions are swapped, i.e., for x(i, j, k), j is the spanwise direction and k is the blade-to-blade direction.

Scaling Parameters

The inlet, exit, hub, tip, and blade coordinates can be rescaled and translated using the following parameters. Flags *bcscale* and *htscale* tell whether to modify the boundary condition and hub and tip coordinates.

bcscale	= 1 Rescale inlet and exit coordinates using *zscale, rscale,* and *ztrans*.
	= 0 Do not rescale inlet and exit coordinates <default>.
htscale	= 1 Rescale hub and tip coordinates using *zscale, rscale,* and *ztrans*.
	= 0 Do not rescale hub and tip coordinates <default>.
zscale	Scale factor for z-coordinates, <default = 1.>
rscale	Scale factor for r-coordinates, <default = 1.>
ztrans	Translation distance for z-coordinates, <default = 0.>

Blade θ-coordinates can be rescaled, translated, and flipped.

tscale	Scale factor for blade θ-coordinates, rarely used. <default = 1>.
ttrans	Translation distance for blade θ-coordinates in radians. Useful for rotating arbitrary blade coordinates to vertical. <default = 0>.
tflip	Flag for flipping the blade in the θ-direction and reordering the points. Important for setting correct blade orientation in multistage machines.
	= 0 Do not flip blade θ-coordinates, <default>.
	= 1 Flip blade θ-coordinates.

Outer Boundary Shape Control Parameters

dslap	i- (streamwise) spacing at exit of C-grid. If *dslap* > 0, the grid lines at i = 2 and i = im-1 are repositioned exactly *dslap* from the exit, overriding *dswex*. For multistage machines the next blade row should have *dsmax* = *dslap* to give a perfect overlap of the grids.
exl, exr	Controls the shape of the left (upstream) or right (downstream) periodic boundaries of a C-grid. The boundaries start tangent to the mean camber line and curve to axial at a rate determined by *exl* or *exr*.

	> 10 No curvature – the boundary is a linear extension of the mean camber line.
	> 1.5 Slow curvature to axial.
	= 1.5 Moderate curvature to axial <default.>
	< 1.5 Fast curvature to axial.
	= 1 Turns the boundary abruptly to axial.
fswake	Fractional distance along the downstream periodic boundary between the trailing edge and the grid exit, where the j-grid lines from the trailing edge *(i = itl)* intersect the outer boundary, (Fig. 1). The default value of <1.0> places the outer boundary points directly above and below the trailing edge point. On some blades this can cause the j-grid lines to cross the trailing edge. In this case try setting *fswake < 1.0* to pull the grid lines towards the downstream boundary.
ioble	The periodic outer boundary for a C-grid is made up of three segments, an upstream segment, the mean-camber line between the blades, and a downstream segment. The parameter *ioble* is an index that determines where the upstream segment joins the mean camber line. Values can be 11, 10, 9, etc. The default <11> starts the upstream segment at the leading edge. Smaller values move the starting point inside the passage, which can be useful if upstream part of the C-grid becomes distorted due to high stagger, (Fig. 1).
iwakex	Flag for stretching the outer boundary grid spacing along the wake (i-direction).
	= 0 Equally-spaced outer boundary along the wake.
	= 1 Stretched outer boundary along the wake, <default>.
jwakex	Flag for controlling the j-direction spacing along the trailing edge cut.
	= 0 j-grid spacing is *dsmin* all along the trailing edge cut, <default>.
	= 1 j-grid spacing expands quickly from *dsmin* at the trailing edge to equally-spaced at the exit.
	= 2 Like jwakex = 1, but the expansion is more gradual.

Hub, Tip, and Blade Input

Immediately following the namelist input are unformatted reads for a title, the hub and tip coordinates, and the blade coordinates. Unformatted ASCII reads are used throughout.

Title

A title of 80 characters or less is read using the following Fortran input statement:

```
read *,ititle
```

ititle	An alphanumeric string of 80 characters that is printed to the output. The character string must be enclosed in single quotes.

Hub and Tip Geometry

Hub and tip coordinate arrays are shown in Fig. 3, and read in as follows:

```
!       read hub & tip geometry
        read(5,*)nph,npt
        read(5,*)(zhub(i),i=1,nph)
        read(5,*)(rhub(i),i=1,nph)
        read(5,*)(ztip(i),i=1,npt)
        read(5,*)(rtip(i),i=1,npt)
```

nph	Number of input hub points, min = 2, max = 321.
npt	Number of input tip points, min = 2, max = 321.
zhub, rhub	z, r coordinates of the hub.
ztip, rtip	z, r coordinates of the tip.

Blade Geometry

The next line of input contains three variables read as follows:

```
!       blade input
        read(5,*)nbs,npb,nblade
```

nbs	Number of blade sections, max. = 50.
npb	Number of points around the blade, max. = 321.
nblade	Number of blades around the wheel, used to determine the pitch.

This is followed by blade coordinates in one of four formats set by the input value of *merid*. The coordinates need not intersect the hub and tip coordinates – they are spline fit if they span the endwalls, or are linearly extrapolated if they do not, and the intersections are calculated by TCGRID. The four input options and their corresponding Fortran reads are as follows:

***merid* = 0 <default>**

Blade input in general stacked sections. Cylindrical coordinates starting at the blade trailing edge, wrapping clockwise around the blade, and repeating the trailing edge point. Complete definition of the leading- and trailing edges must be given. Sections are stacked from hub to tip. Fig. 5 shows the ordering of points for *merid* = 0.

```
!      merid=0: blade input in stacked sections, cyl. coords.
       if(merid == 0)then
       do k=1,nbs
         read(5,*)(zb(i,k),i=1,npb)
         read(5,*)(yb(i,k),i=1,npb)
         read(5,*)(rb(i,k),i=1,npb)
       enddo
       endif
```

Here (zb, yb, rb) = (z, θ, r)-coordinates of the blade section.

***merid* = 1**

Blade input in Crouse/Tweedt design code format. See Tweedt's writeup on design code options. The point ordering around the blade is the same as for *merid* = 0, as shown in Fig. 5, but the points are stacked from tip to hub.

```
!      merid=1: blade input in Crouse/Tweedt design code format
       if(merid == 1)then
       read(5,*)zbhub
       do k=nbs,1,-1
         read(5,*)dum
         read(5,*)dum
         read(5,*)(zb(i,k),i=1,npb)
         read(5,*)(yb(i,k),i=1,npb)
         read(5,*)(rb(i,k),i=1,npb)
       enddo
       endif
```

Again (zb, yb, rb) = (z, θ, r)-coordinates of the blade section.

zbhub	A z-translation value added to all blade z-coordinates, to shift them to the same reference as the hub and tip. Can also be done using namelist variable *ztrans*.
dum	Two dummy records are included before each blade section.

***merid* = 2 or 3**

Blade input in MERIDL format. See Katsanis and McNally's report on MERIDL [3] for more information on MERIDL input. Unlike MERIDL, TCGRID can handle purely radial flows without rotating the coordinate system. MERIDL input has no leading- or trailing edge definition, but TCGRID will add leading- and trailing edge circles automatically. Points are input from leading edge to trailing edge, and from hub to tip.

```
!      merid=2 or 3: blade input in MERIDL format
       if(merid > 1)then
       do k=1,nbs
         read(5,*)(  zbl(i,k),i=1,npb)
       enddo
       do k=1,nbs
         read(5,*)(  rbl(i,k),i=1,npb)
       enddo
       do k=1,nbs
         read(5,*)(th1bl(i,k),i=1,npb)
       enddo
       do k=1,nbs
         read(5,*)(th2bl(i,k),i=1,npb)
       enddo
       endif
```

merid = 2	(zbl, rbl, th1bl, th2bl)= (z, r, θ-upper-surface, θ-lower-surface) coordinates of the blade section, (Fig. 6).
merid = 3	(zbl, rbl, th1bl) = (z, r, θ)-coordinates of the mean-camber-line, ordered like *merid* = 2 (Fig. 6.),
	th2bl = blade tangential thickness (θ-upper-surface – θ-lower-surface).

Grid Output *XYZ*-File

Grids are stored using standard PLOT3D xyz-file structure. Single block grids can be read with the following code:

```
      read(1)im,jm,km                         !grid dimensions
!     read grid coordinates
      read(1)
     &(((x(i,j,k),i=1,im),j=1,jm),k=1,km),
     &(((y(i,j,k),i=1,im),j=1,jm),k=1,km),
     &(((z(i,j,k),i=1,im),j=1,jm),k=1,km)
```

Multiblock grids can be read with the following code:

```
      integer,dimension(3,10)::idx

      read(1)ngrid                            !number of grids
      read(1)((idx(l,ng),l=1,3),ng=1,ngrid)   !grid dimensions
!     loop over the grids
      do ng=1,ngrid
        im=idx(1,ng)
        jm=idx(2,ng)
        km=idx(3,ng)

        read(1)
     &  (((x(i,j,k),i=1,im),j=1,jm),k=1,km),
     &  (((y(i,j,k),i=1,im),j=1,jm),k=1,km),
     &  (((z(i,j,k),i=1,im),j=1,jm),k=1,km)
      enddo
```

TCGRID Code Description

Grids are generated in several sequential steps. Most steps are coded as separate subroutines, many of which can generate PLOT3D compatible grid files for debugging purposes. The outline below lists the main subroutines of TCGRID, describes their function, and describes any debug files that can be generated. Indentation implies subroutine nesting.

Debug files are requested using the namelist array *idbg*(9) described in Table 1 on page 22. In general, if *idbg*(n) = 1, a debug grid file will be generated on Fortran unit n+10. Grids are in PLOT3D format, may be 2-D or 3-D, and may be in multigrid format. If there is a problem with TCGRID, set *idbg* = 9*1 and plot fort.11 – fort.19 in turn. (Some files may not be generated depending on input options.) Refer to the outline below to determine at which step the problem occurred.

tcgrid.f

Main calling program.

1. **setup.f**
   Reads the namelist, hub, tip, and blade input. Hub and tip geometries are input as arrays of (z,r) coordinates. Blade geometries are input as arrays of (z,r,θ) coordinates. Several blade input formats are supported. The blade coordinates can be scaled and translated if desired.
   Output file: *idbg*(1) = 1, fort.11, 3-D blade as input (*merid* = 0 or 1), or blade after addition of leading- and trailing edge circles (*merid* = 2 or 3.)
   openfile.f - Opens files by name if *iopen* = 1.

2. **inner.f (*merid* = 0 or 1)**
   Reclusters points around the blade sections. The leading and trailing edges are evenly spaced. The trailing edge spacing is centered about the first blade input point (which is repeated as the last input point unless *nbase* > 0.) The leading- edge spacing is centered about some fraction of arc length specified using *dsra*. If *dsra* = 0.0, the leading edge spacing is centered about the median input point. The blade surfaces are reclustered between the leading and trailing edges using Hermite polynomials or hyperbolic tangent clustering. Inner.f also adds points on the base if *nbase* > 0.

3. **merfix.f (*merid* = 2 or 3)**
   Converts MERIDL blade sections to GRAPE-type sections. Adds leading and trailing edge circles. Adds points on the base if *nbase* > 0. Reclusters points around the blade sections.
   Output file: *idbg*(2) = 1, fort.12, 3-D multigrid MERIDL blade as input (*merid* = 2 or 3).
   lete.f - Computes leading- and trailing edge circles for the MERIDL blades using the technique in [4].

4. **addht.f**
   Adds inlet and exit points to hub and tip arrays.

5. **meridg.f**
   Generates a coarse meridional grid between the hub and casing. The grid is generated algebraically by connecting corresponding points on the hub and casing. The number of spanwise points should be about the same as the number of input blade sections. If *iclus2d* = 0 the meridional grid is equally spaced spanwise. This option is good for simple ruled blades or blades defined on equally spaced stream surfaces. If *iclus2d* = 1 the meridional grid is generated with approximately the same spanwise clustering as the input blade sections.
   Output file: idbg(3) = 1, fort.13, 2-D meridional grid between hub and tip.

6. **blades.f**
   Intersects spanwise lines between blade sections with the streamwise lines of the meridional grid. This gives new blade sections on the stream surfaces defined by the meridional grid.
   Output file: *idbg*(4) = 1, fort.14, 3-D blade after interpolation onto meridional grid.

7. **grid2d.f**
Generates 2-D blade-to-blade grids along the meridional grid lines using an updated version of the Steger/Sorenson GRAPE code [5, 6]. GRAPE is strictly 2-D, so the 3-D blade sections are mapped to a 2-D $(m,\bar{r}\times\theta)$ system, where *m* is the meridional coordinate defined by $dm^2 = dz^2 + dr^2$, and $\bar{r}$ is the mean radius.

GRAPE requires the specification of an inner and outer boundary. For a C-grid the inner boundary is defined by the mapped blade coordinates plus a polynomial wake cut. A periodic outer boundary is defined using the mean camber line inside the passage, with polynomial extensions up- and downstream. For an H-grid the boundaries are defined by the blade surfaces and polynomial extensions up- and downstream. Angles and spacings are specified on the boundaries. The angles are set to give normal grid lines at the blade and inlet, and vertical grid lines at the periodic boundaries. The spacings are input using *dsmin* and *dsmax*.
outc.f - Generates the periodic boundary for a C-grid
outh.f - Generates the periodic boundary for a H-grid

An initial grid is generated algebraically. GRAPE uses an SLOR scheme to solve the Poisson equations, and is typically iterated 50 – 150 iterations. Dummy grid lines may be added algebraically.
Output file: idbg(5) = k, unit 15, 2-D blade-to-blade grid on surface k of the meridional grid.
grelax.f - Solves the elliptic grid equations.
dumgl.f - Adds dummy grid lines if *iswift* = 1.

Finally the 2-D $(m,\bar{r}\times\theta)$ grid is transformed back to (z,r,θ) .
Output file: *idbg*(6) = 1, unit 16, 3-D grid before spanwise clustering.

8. **fill3d.f**
Reclusters the 2-D grids spanwise using either Hermite polynomials or hyperbolic tangent clustering to make the final 3-D grid. Separate clustering functions are used in the hub clearance, blade, and tip clearance regions.

9. **ginlet.f**
Generates an algebraic H-block upstream of the blade if *igin* = 1. The boundaries are defined by the hub and casing, and the inlet boundaries of the H-grid and C-grids. Transfinite interpolation [7] is used to fill in the interior points. The resulting meridional grid is swept tangentially.
Output file: idbg(7) = 1, unit 17, 3-D inlet H-grid.

10. **gtip.f**
Generates an algebraic O-grid block in the tip clearance region if *igclt* = 1.
Output file: idbg(8) = 1, fort.18, 3-D tip clearance O-grid.
Generates an algebraic O-grid block in the hub clearance region if *igclh* = 1.
Output file: idbg(9) = 1, fort.19, 3-D hub clearance O-grid.

11. **ospan.f**
Prints the inlet, leading edge, trailing edge, and exit coordinates.

12. **outmg.f**
Transforms (z,r,θ) coordinates to (x,y,z) and writes the grid file to fort.1 in PLOT3D format.
Output file: fort.1, 3-D grid.
Output file: fort.10, ASCII index file for use by the SWIFT code. Contains grid sizes and indices that may be needed for other codes.

Debug Output Files

Table 1. Debug grid files available by the *idbg(i)* parameter.

Index	Value	Unit	Subroutine	Grid Size	PLOT3D Format	Grid Description
1	1	11	Input	(npb, nbs, 1)	3d/unf	General blade as input (*merid* = 0, 1) MERIDL blade after l.e. & t.e. addition (*merid* = 2, 3)
2	1	12	Merfix	(nbs, npb, 1)	3d/unf/mg	MERIDL blade as input (*merid* = 2, 3)
3	1	13	Meridg	(i2d, k2d)	2d/unf	2-D meridional grid between hub and tip
4	1	14	Blades	(npb, k2d, 1)	3d/unf	3-D blade after interpolation onto 2-D grid
5	k	15	Grid2d	(im, jm, 1)	2d/unf	2-D blade-to-blade grid on section k
6	1	16	Grid2d	(im, km,k2d)	3d/unf	3-D grid before spanwise clustering
7	1	17	Ginlet	(imi, jmi, kmi)	3d/unf	3-D inlet H-grid
8	1	18	Gtip	(imt, jmt, kmt)	3d/unf	3-D tip clearance O-grid
9	1	19	Gtip	(imh,jmh,kmh)	3d/unf	3-D hub clearance O-grid

Several intermediate grid files that may be useful for input checking, geometry manipulation, or debug, can be output from TCGRID. Intermediate grid output is triggered by setting elements of input array *idbg(9)* in namelist &nl3. Output files are written as unnamed binary files in PLOT3D format, to Fortran unit *idbg_index + 10*. Table 1 gives the output files associated with each element of *idbg*. Possible uses for the output files are described below.

Examining input files

Set idbg(1) = 1 or idbg(2) = 1 to see the blade shape as input on fort.11 or fort.12.

Checking the meridional grid

Set idbg(3)=1 to see the meridional grid on fort.13.

Geometry Manipulation

Set idbg(4) = 1 to add leading and trailing edges to MERIDL files, and intersect the blade with the hub and tip. The modified blade shape on fort.14 could be a good starting point for another grid code.

Debugging the grid generation process

Set idbg(5) = k (2-D plane that you want to see.)

Set *iterm* = 0 to run zero iterations. Look for crossed grid lines or bad spacings in the 2-D grid on fort.15. Set *iterm* > *0* to see the effects of the elliptic smoother.

Acknowledgments

Joe Steger and Reece Sorenson developed and supplied the original GRAPE code that serves as the basic grid solver in TCGRID. Kevin Kirtley developed an early version of TCGRID called GRD3D. Larry Schuman provided the algorithm for adding leading edge circles to MERIDL blades. Dan Tweedt developed the spline routines used in TCGRID and provided many helpful comments and suggestions. Hung Huynh developed the monotone splines used in version 305. Dave Miller provided the transfinite interpolation routine used for the upstream grid block.

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2. Chima, R. V., Giel, P. W., and Boyle, R. J., "An Algebraic Turbulence Model for Three-Dimensional Viscous Flows," in *Engineering Turbulence Modelling and Experiments 2*, Rodi, W. and Martelli, F. editors, Elsevier pub. N. Y., 1993, pp. 775-784. Also NASA TM-105931.

3. Katsanis, T., McNally, W. D., "Revised Fortran Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct," NASA TN D-8430, Mar. 1977.

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7. Thompson, J. F., Warsi, Z. U. A., Mastin, C. W., *Numerical Grid Generation Foundations and Applications*, North-Holland, N. Y., 1985.

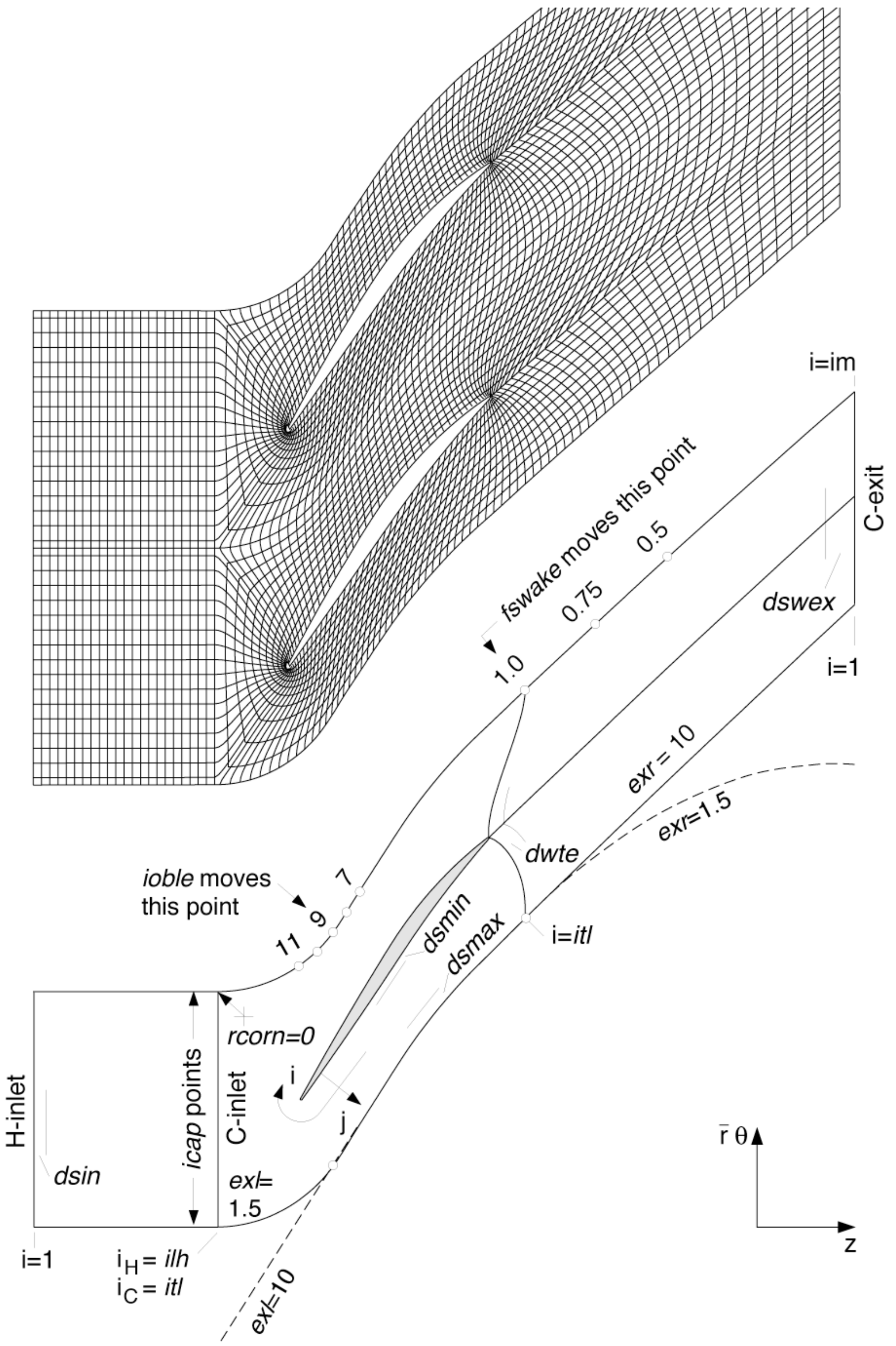


Figure 1. Top – Blade-to-blade H-C grid for a compressor blade tip section. Bottom: TCGRID nomenclature and input variables for blade-to-blade grids.

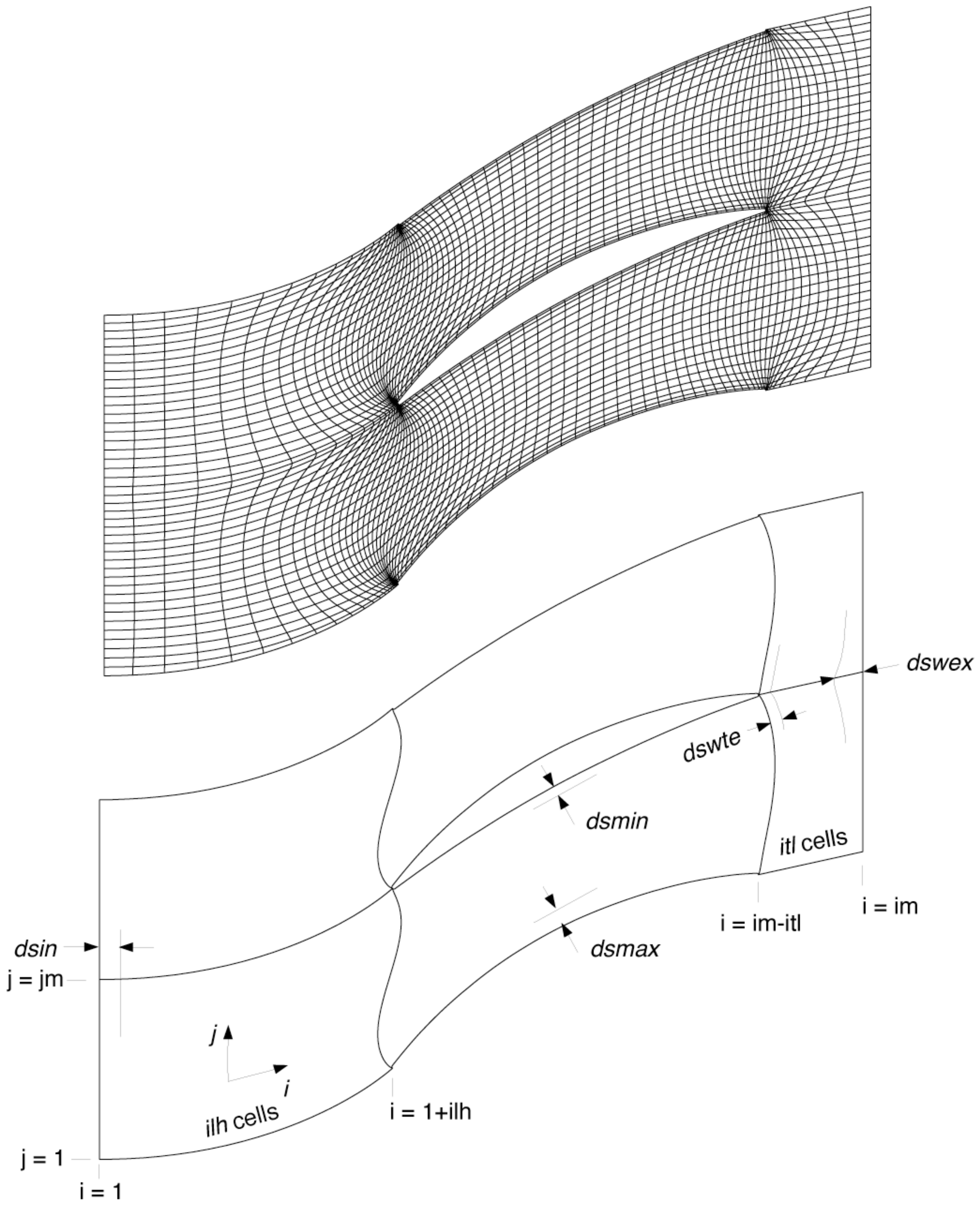
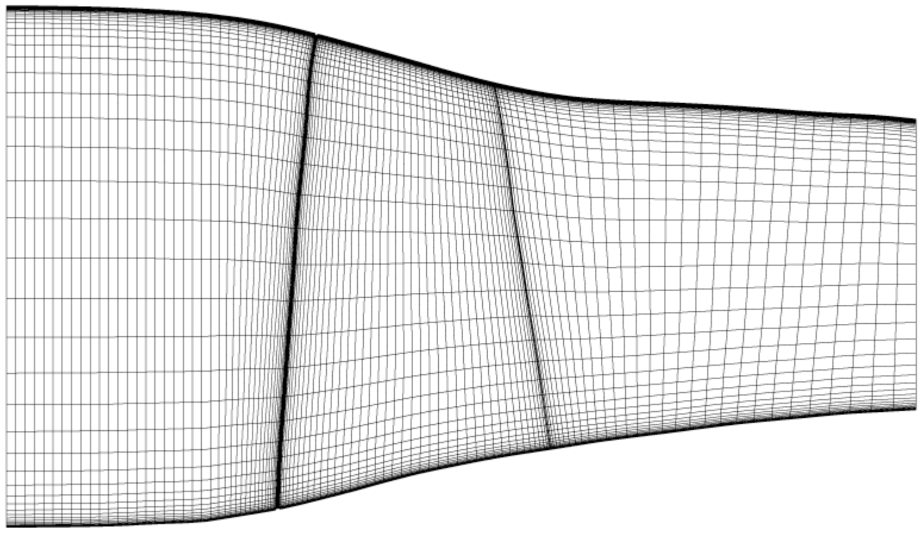


Figure 2 Top – Blade-to-blade H grid for a compressor blade hub section.
Bottom: TCGRID nomenclature and input variables for H-grids.



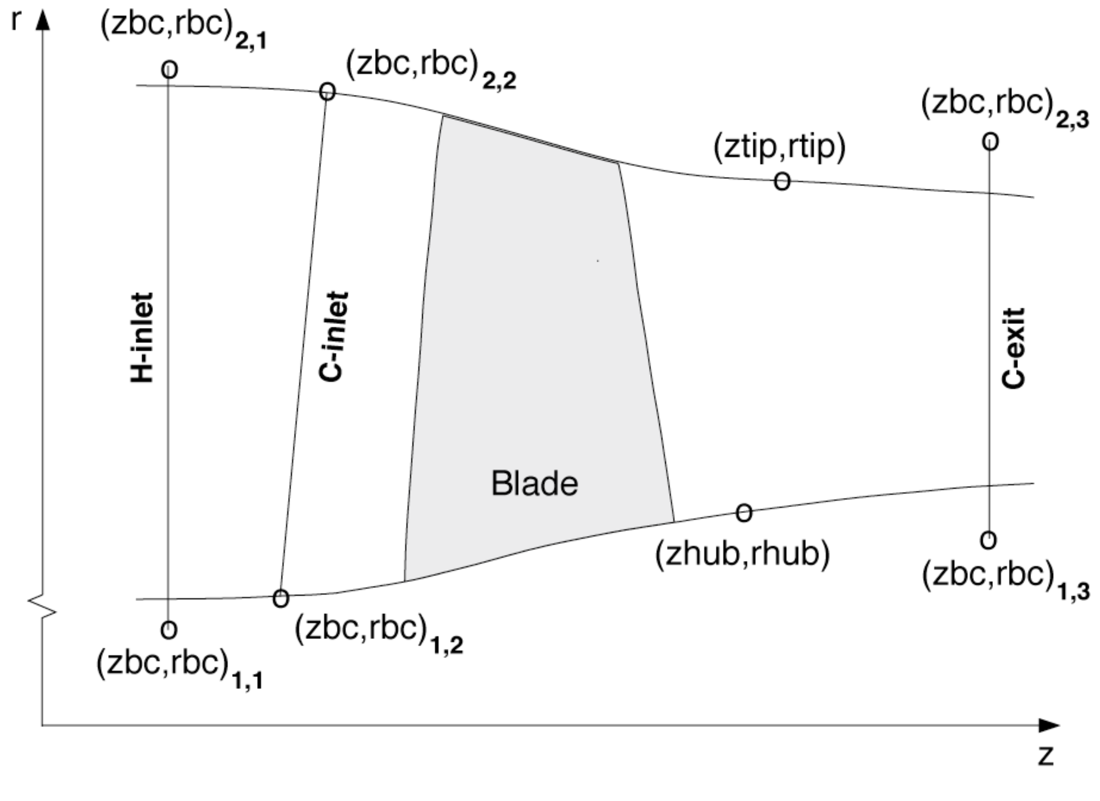
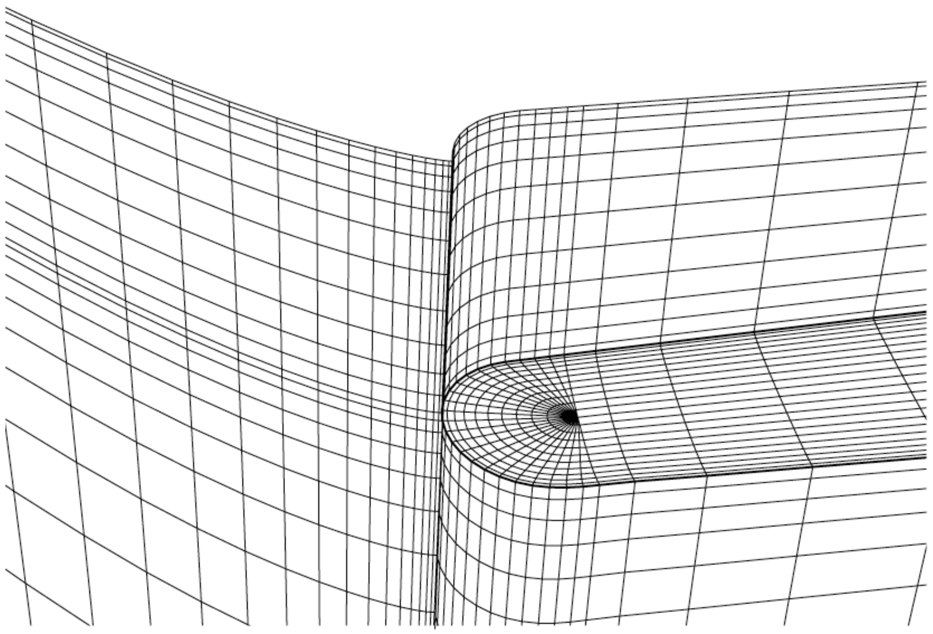


Figure 3 – Top: Meridional H-C grid for compressor blade.
Bottom: TCGRID nomenclature and input variables for meridional grids.



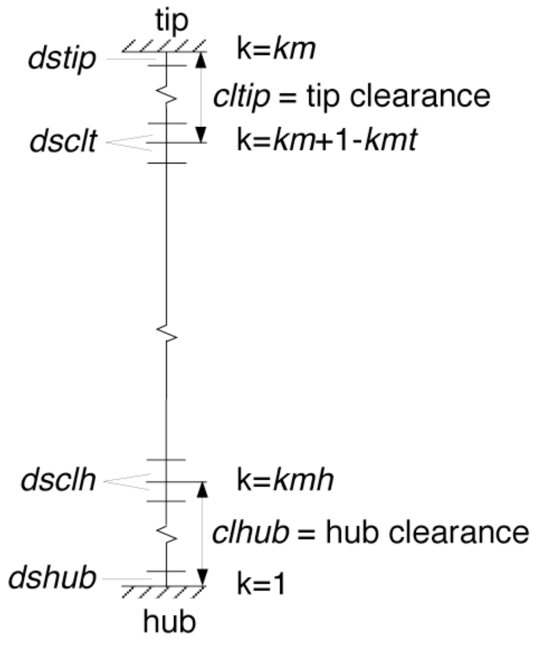


Figure 4 – Top: Tip clearance O-grid for a compressor blade.
Bottom: TCGRID nomenclature and input variables for the spanwise grid.

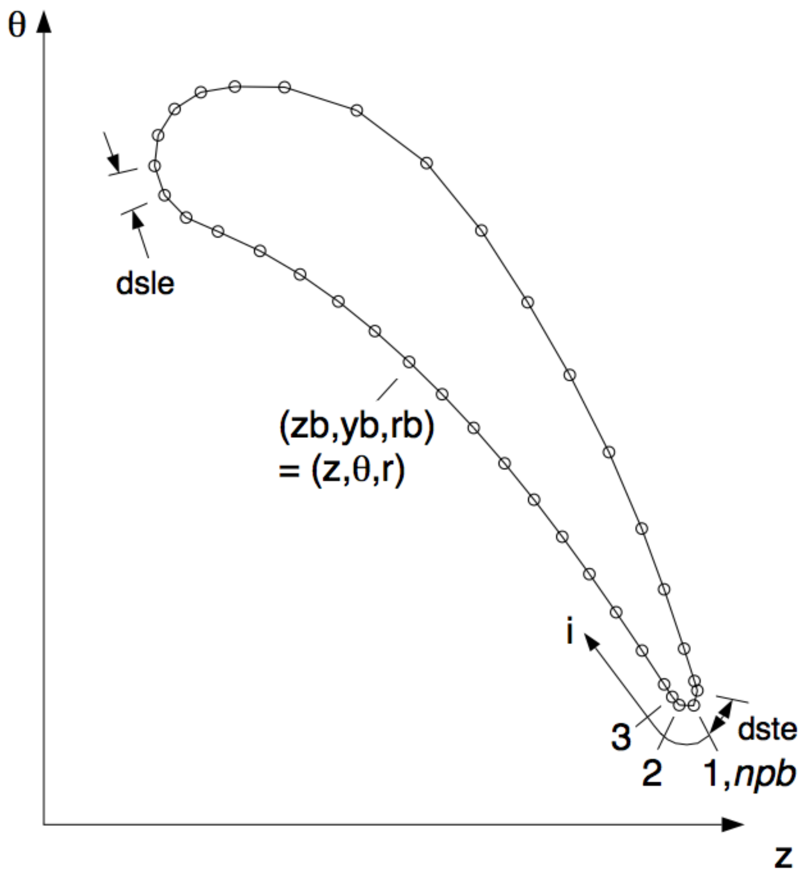


Figure 5 – Blade coordinate input variables for *merid* = 0 or 1, with leading and trailing edge spacing parameters.

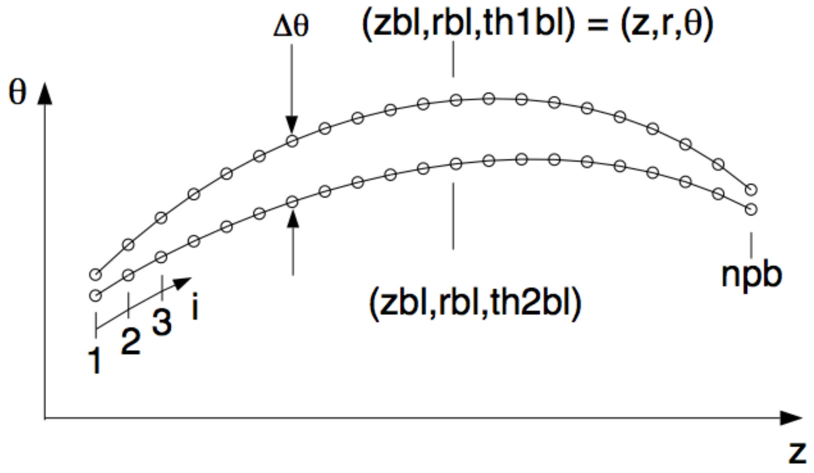
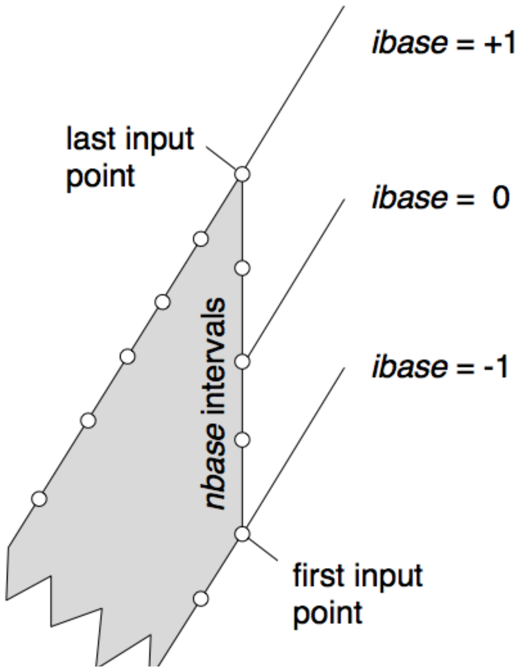
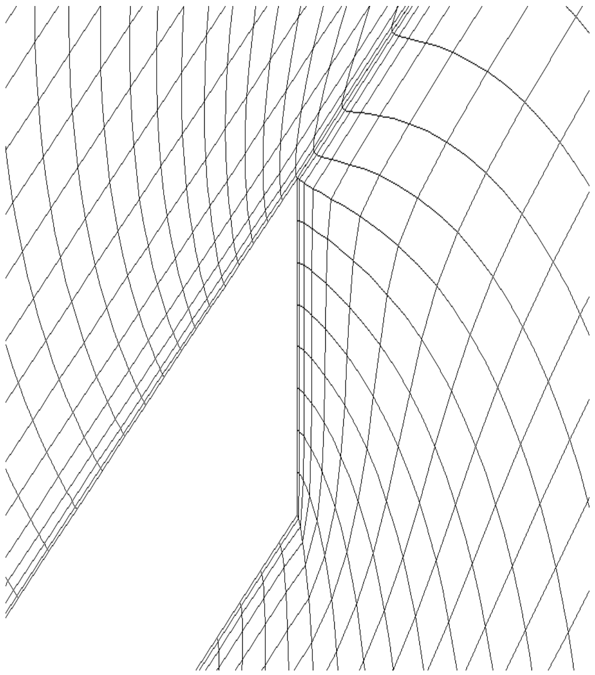
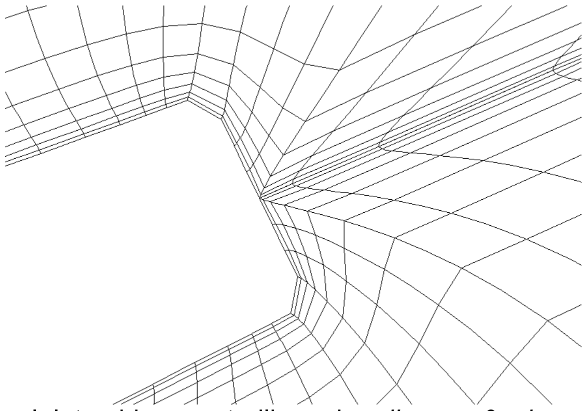


Figure 6 – Blade coordinate input variables for *merid* = 2 or 3.



a. Effect of *ibase* on location of wake cut.


b. Centrifugal impeller trailing edge, *ibase = 1, nbase = 8, ibevel = 0*.


c. Inlet guide vane trailing edge, *ibase = 0, nbase = 8, ibevel = 1*.

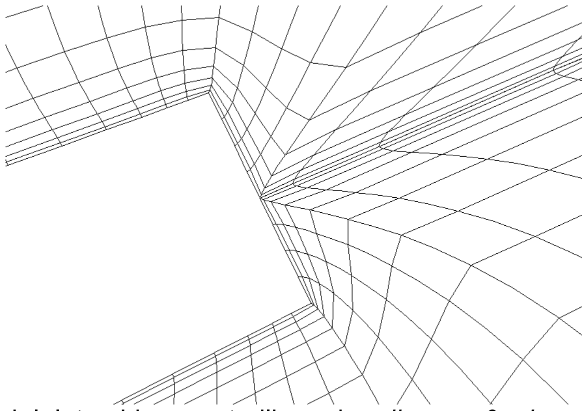

d. Inlet guide vane trailing edge, *ibase = 0, nbase = 8, ibevel = 0*.

Figure 7 – Options for blunt trailing edges.