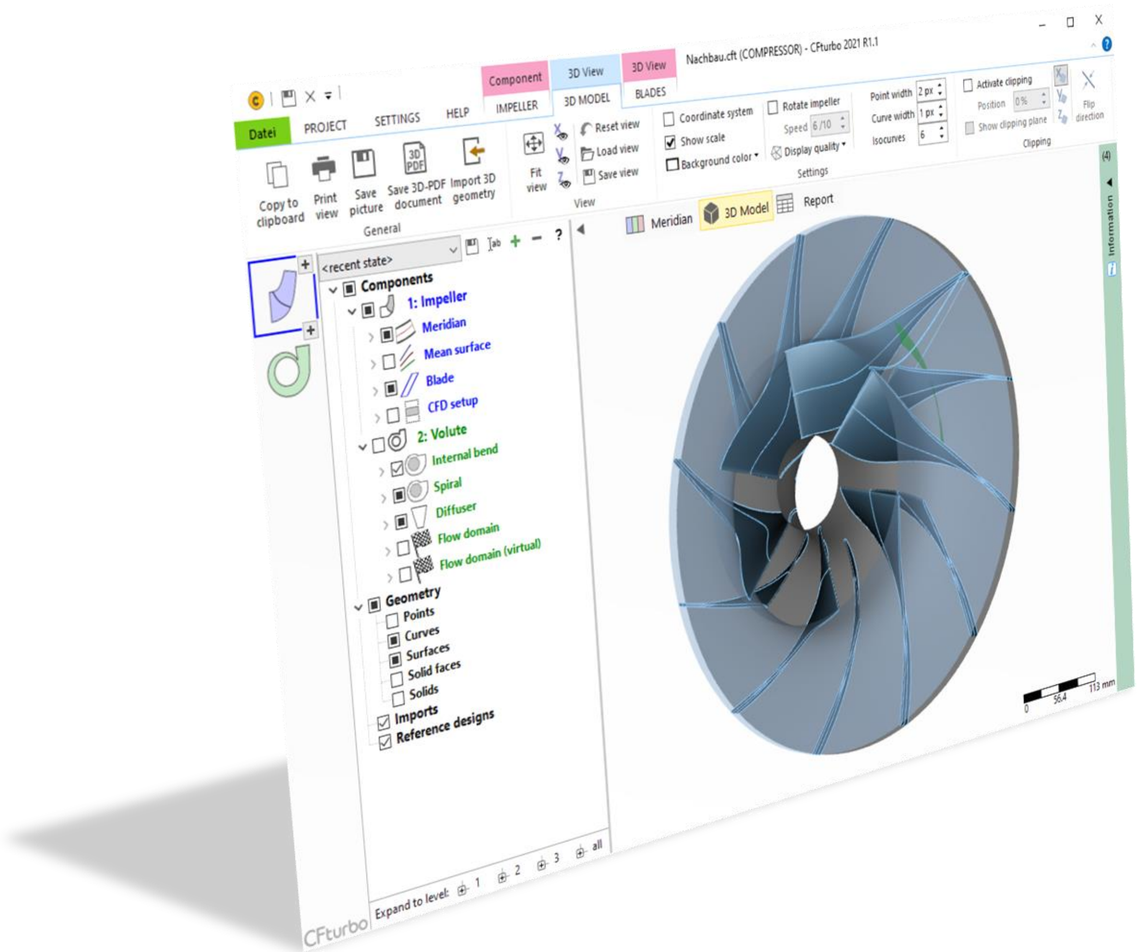
CFturbo

Instruction on the reverse design of a turbomachine with CFturbo on the example of a compressor



Content

1 Preliminary

1.1 Assumption of best point and fluid properties

Empirical functions are implemented in CFturbo that allow the calculation of parameters based on the specific speed for instance. Therefore, the opportunity is given to set up parameters in a way that a promising design will be created. Here promising may stay for the fact that a good efficiency will be gained with the design.

The consideration of the empirical correlations may also be advantageous while reversely redesign a given geometry of an impeller. Therefore, the following parameters should be given:

- Fluid properties
- Design point mass flow
- Design point speed
- Design point pressure ratio
- Inlet conditions
- Direction of rotation
- Casing efficiency for considering additional losses in stators and volute

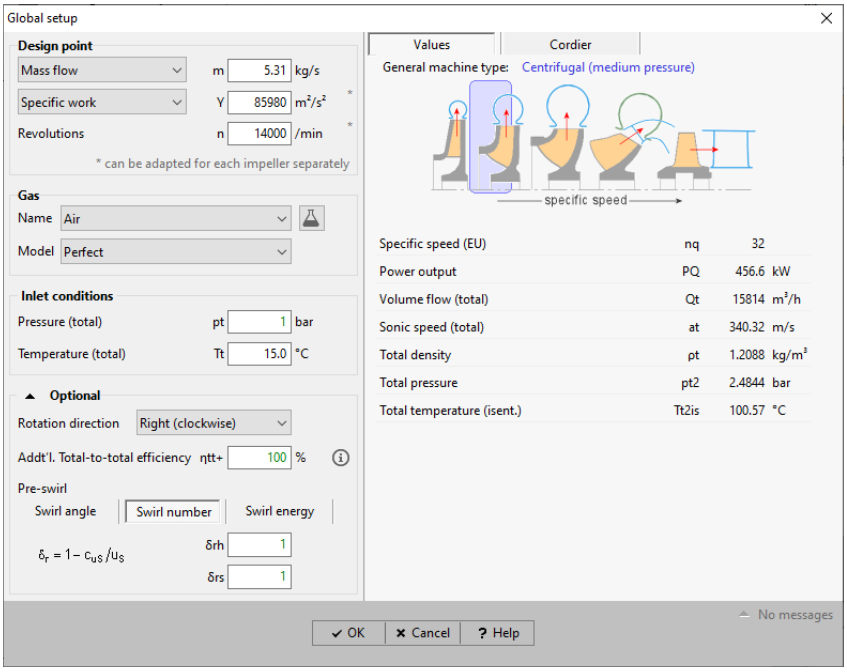


Figure 1

In case of pumps or blowers there is not a fluid property model combo box. Then only the density of the fluid must be given or chosen from the data base respectively.

1.2 Setup of the main dimensions of the impeller

The main dimensions, that are hub and shroud diameter (d_H, d_S) as well as outlet width (d_2, b_2), must be taken from the geometry of the given impeller and must be input in the design step "Main dimensions" tab 3:

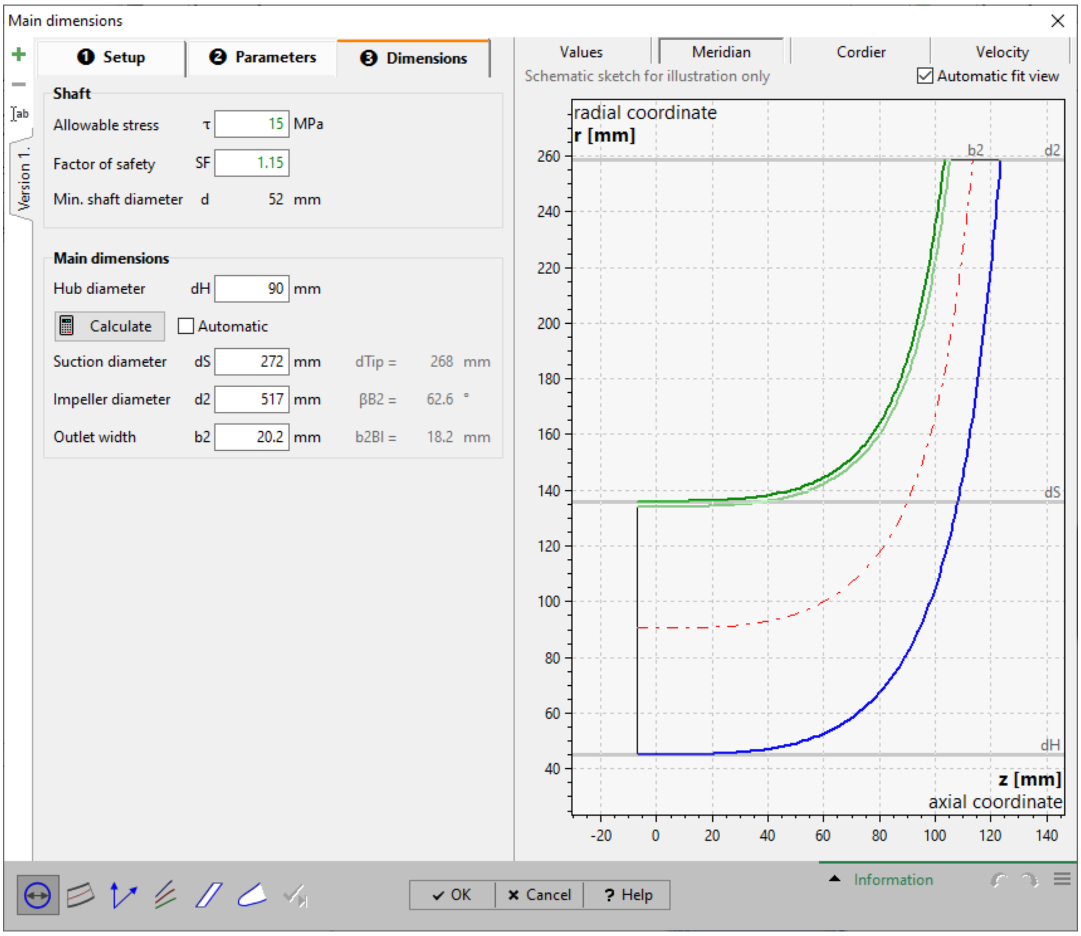


Figure 2

The mode "automatic" is to be deactivated. Beyond the mentioned parameter, further dimensions must be taken from the original geometry and must be typed in (tab 1):

- the size of the tip
- splitter blades

2 Geometric design of the impeller

2.1 Generation of reference geometries

The original geometry of the impeller should be visible in CFturbo while conducting the reverse engineering. Therefore, a visual comparison is possible. To this end reference data of the impeller must be created, that are hub and blades:

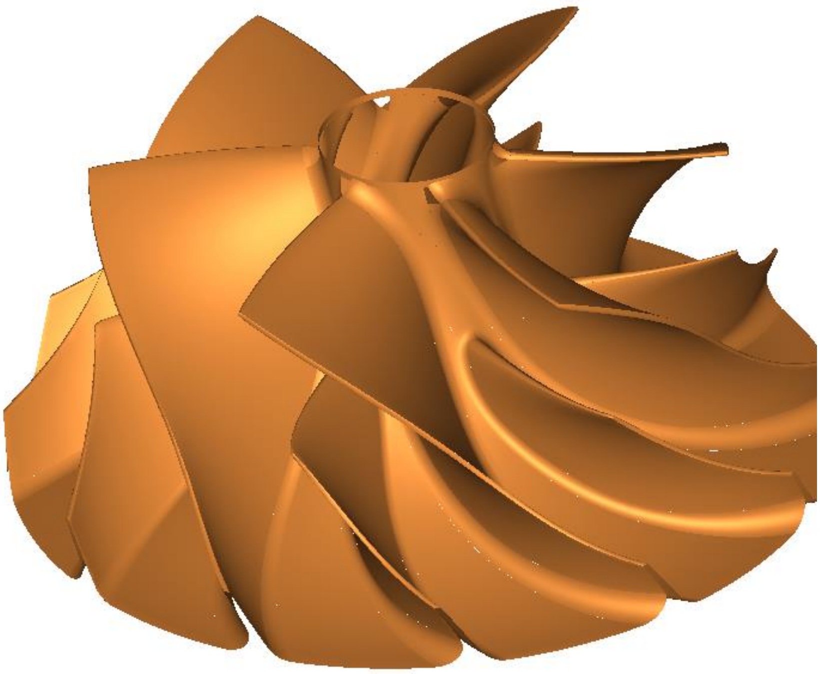


Figure 3

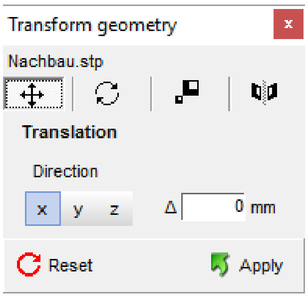


Figure 4

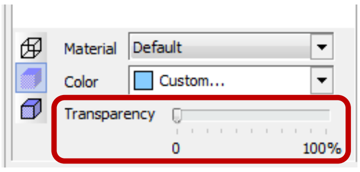


Figure 5

Geometries can be loaded into the current design in neutral formats like IGES, STEP and STL. The extracted impeller should be saved in one of these formats. STL shall be only the second choice because this needs comparatively more memory. The impeller must be aligned in x- and y-direction in a way as demanded by CFturbo. Currently in CFturbo the displacement of imported geometries is possible only in z-direction and the rotation is only possible around z-axis (Figure 4).

It is advantageous to display the imported geometry of the impeller transparently. This can be done by selecting the imported impeller (model tree branch "Imports") via left click with the mouse. Subsequently the value of transparency can be changed (e.g. to 40%, see Figure 5).

2.2 Determination of the meridional shape

The meridional cut in the second design step should be based on the co-ordinate z and r (axial length, radius). Therefore, these data must be extracted from the original geometry. Figure 6 shows the impeller geometry and a plane that contains the rotational axis. From surfaces, built by rotation of leading edge of main and splitter blades, intersection lines with the axial plane can be created.

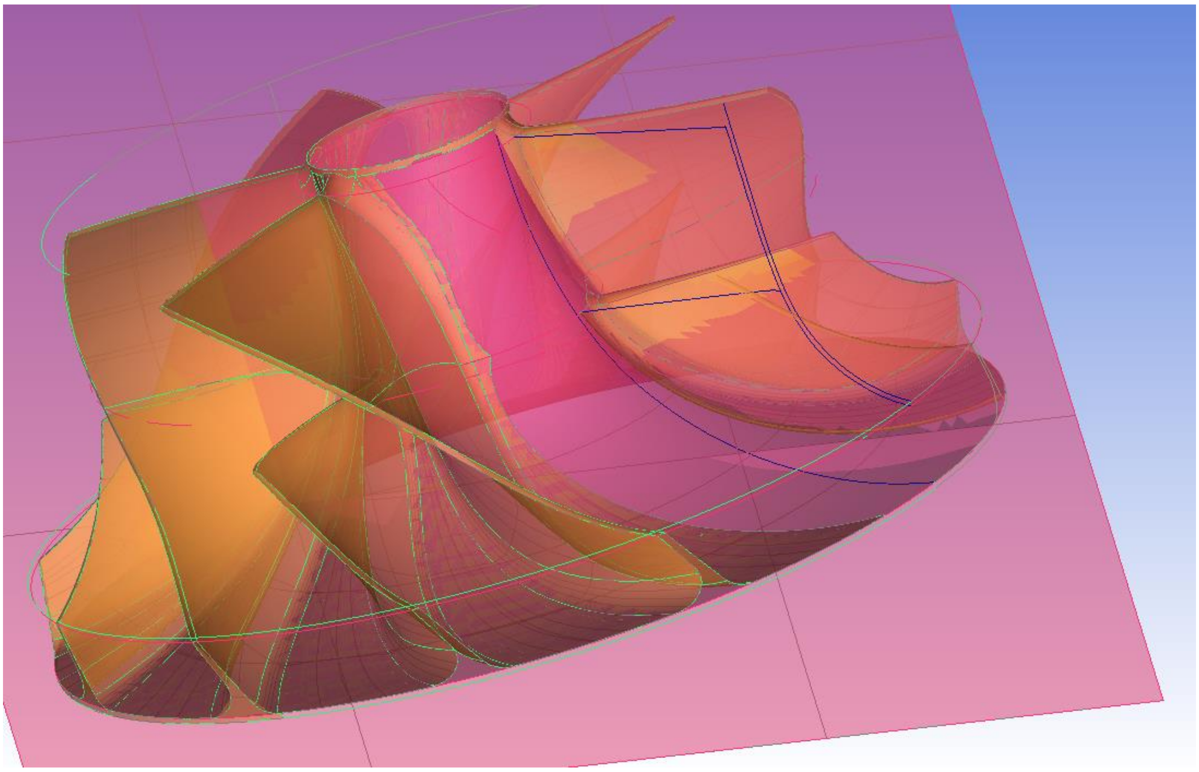
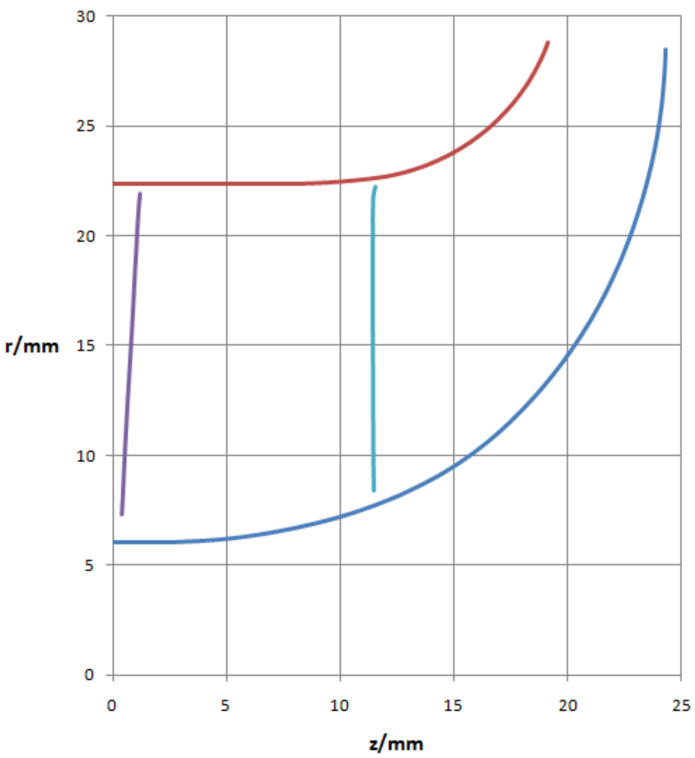


Figure 6

The intersection of hub and shroud with the co-axial plane contains the (hub and shroud) co-ordinates in z and r. The following curves are the result (Figure 7). Their co-ordinates should be saved in a text-file to be loaded into CFturbo. The data have to be given in the unities that are used by CFturbo with current design (here e.g. in mm), a z-r-pair per row:



Example: Hub.txt:

0	6.031548139
0.379575416	6.033787969
0.75914152	6.031430792
1.13870576	6.028328091
1.518281177	6.026141811
1.897860318	6.027228199
...	

Figure 7

After the first call of the design step for the creation of the meridional contour (Meridional contour), a meridional cut will be built in accordance with the default co-relations of CFturbo and according the main dimension earlier set. Now the z-r-co-ordinates of hub etc. should be loaded for comparison. This is done by a right click in the display area and by the subsequent selection of the context menu item "Load extra polyline".

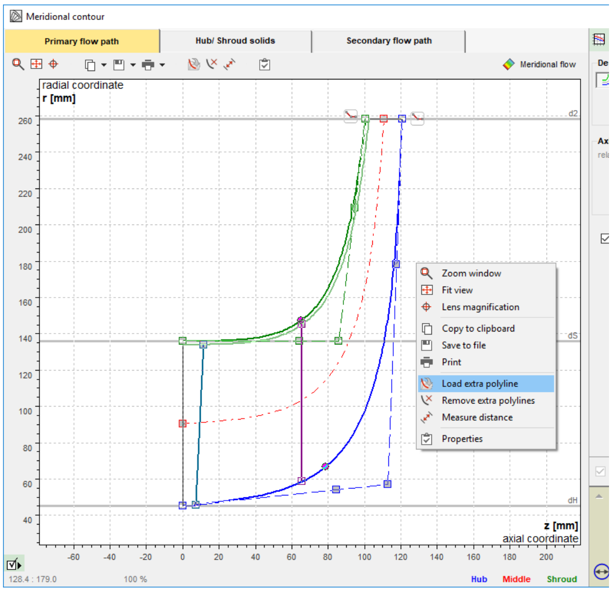


Figure 8

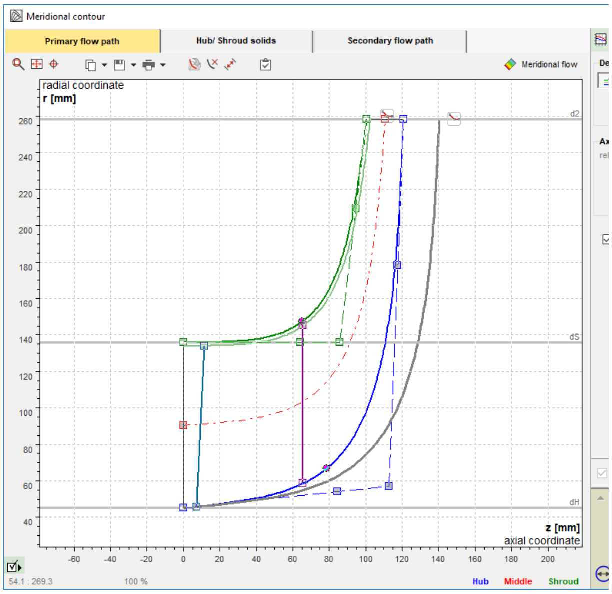


Figure 9

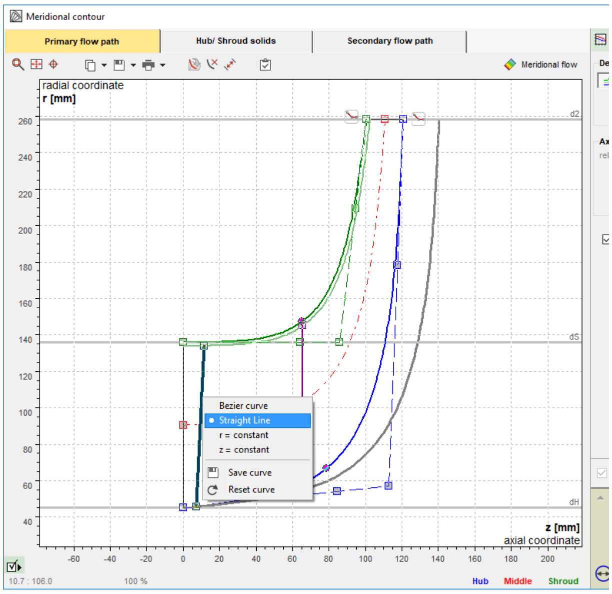


Figure 10

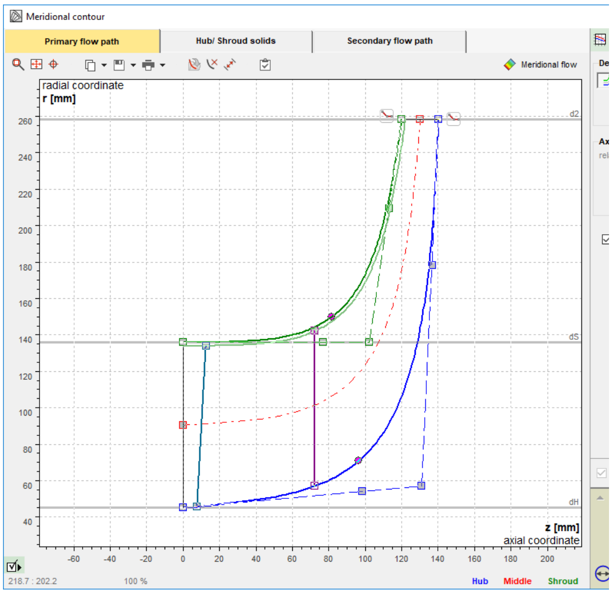


Figure 11

As an example for that a loaded hub line (grey) is displayed in Figure 9. The blue hub Bézier curve must be altered now in a way that it gets almost congruent with the grey line. Due to degree of the Bézier curve (here 4.) there will not be 100% congruence in most of the cases, but good approximations are possible. The most top Bézier point of hub and shroud cannot be shifted in axial direction, since this would change the outlet width. That is way the most top Bézier point of the mid (dotted) Bézier curve must be used to chance the extension of the meridional shape.

As shown for the hub, all other curves of the meridional cut must be adjusted to the reference geometry. This can be done by utilizing the automatic approximation of curves. To this end the menu item “Bézierkurve/Polyline to Bézier…“ must be chosen in the context menu (Figure 12). Afterwards the curve to be approximated must be loaded (Figure 13).

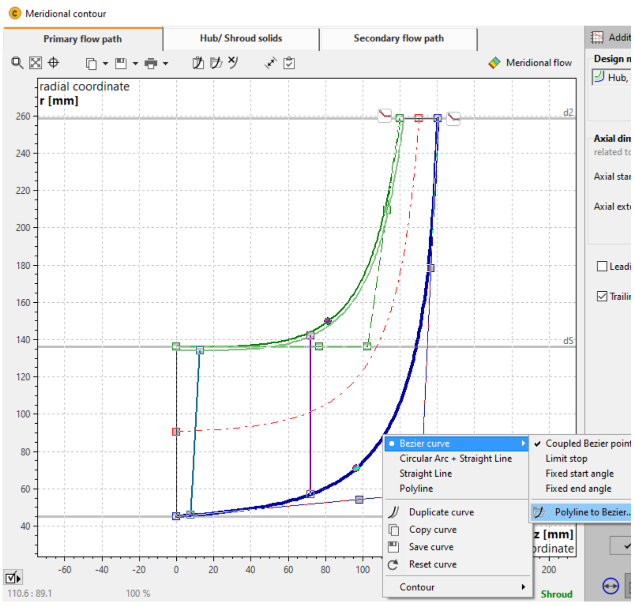


Figure 12

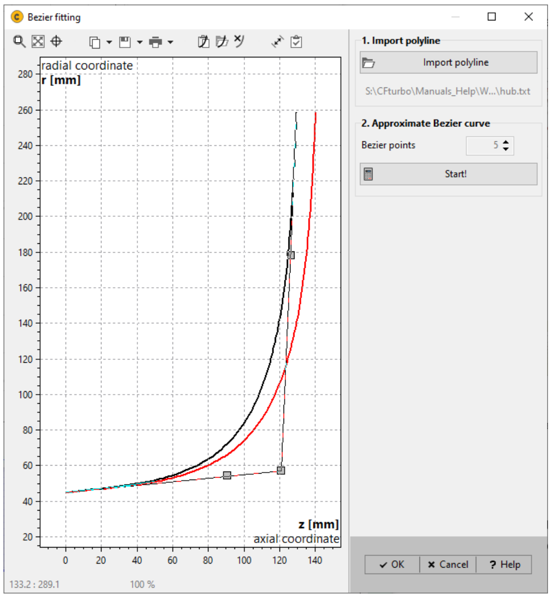


Figure 13

Default for the leading edge is a straight form. In case the leading edge of the reference impeller is not straight, its form must be changed in the meridional contour dialog. This must be done by right clicking on the curve and choosing the proper option in the appearing context menu (Figure 10).

The option "Freeform" yields a 4th degree Bézier curve. With this type of curve, the user has the greatest freedom while designing. However, option "Straight" might be sufficient for most of the contours of the leading edges. After appropriate modifications of the curves the meridional contour given in Figure 11 was created for the actual example.

As in any of the following dialogs (i.e. design steps) the current geometry can and shall be compared visually with the reference geometry by using the 3D-Preview. The comparison might yield the need for further parameter changes.

2.3 Blade properties

2.3.1 Extraction of geometrical dimensions

It is a strong advantage if the geometric variables can be extracted from the basis geometry in a way that they can be used directly in CFturbo. Such variables are e.g. radii, axial length, meridional and tangential co-ordinates as well as blade angles along mean lines, with whose help mean surfaces of the blades can be designed.

Such a line is e.g. the mean line at the tip of the blade. In case the line's x,y,z-co-ordinates are known, the following variables can be easily derived from it:

variable	formula
axial length	z
radius	$r = \sqrt{x^2 + y^2}$
meridional coordinate	$m = \int_{\text{leading edge}}^{\text{trailing edge}} \frac{\sqrt{dr^2 + dz^2}}{r}$
tangential coordinate	$t = \arctan\left(\frac{y}{x}\right) - t_{\text{leading edge hub}}$
blade angle	$\beta = \arctan\left(\frac{dm}{dt}\right)$

Table 1

To be loadable in CFturbo those data must be provided in text files see chapter 2.2, that contain rows of co-ordinate pairs.

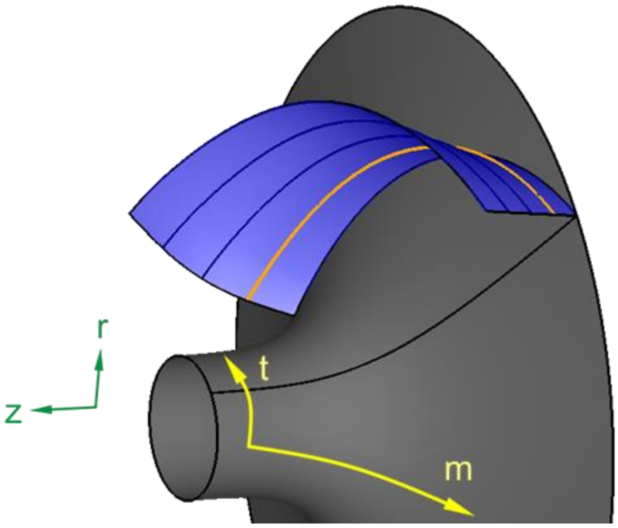


Figure 14

The spatially curved meridional flow surfaces are mapped to a plane by this coordinate transformation. Here t is the angle in circumferential direction whereas m is the dimensionless meridional extension.

Both quantities are created by the reference of absolute distances in meridional (M) and tangential direction (T) to the local radius r:

$dm = \frac{dM}{r}$ und $\quad dt = \frac{dT}{r}$.

2.3.2 Determination of the blade angles at leading and trailing edge

Within this design step the number of spans, which are used to design at, must be determined as well as the blade leading and trailing edge angles at those spans. Beyond it a first estimation of the blade thickness at hub and shroud must be given. These values may be adjusted iteratively later in the process of the reverse design. Therefore, for the time being the thickness definition can be carried out based on CFturbo's defaults. The calculation of the blade angles on this basis will be achieved by the soft button "Calculate β_B (Main)" (Figure 16). When the data have been extracted as described in the prior chapter, blade angles can be taken directly from there.

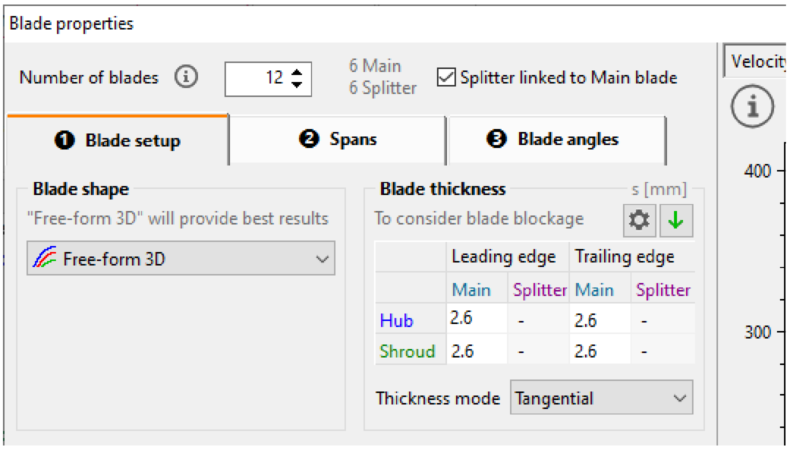


Figure 15

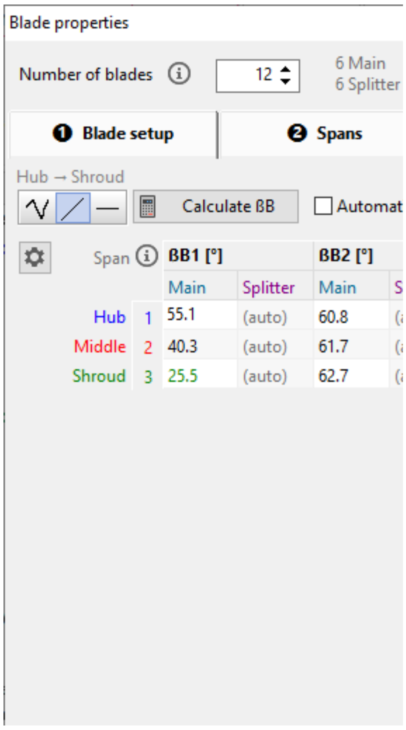


Figure 16

In case of 3D-blading, the option "Free form 3D" must be chosen in the section "Blade setup". It is convenient to design on a small number of spans (blade mean lines), because this will limit the number of parameters to be adjusted. Therefore, with 3D-blading one should try to carry on with the design based on 3 spans.

Furthermore, the number of blades must be set here.

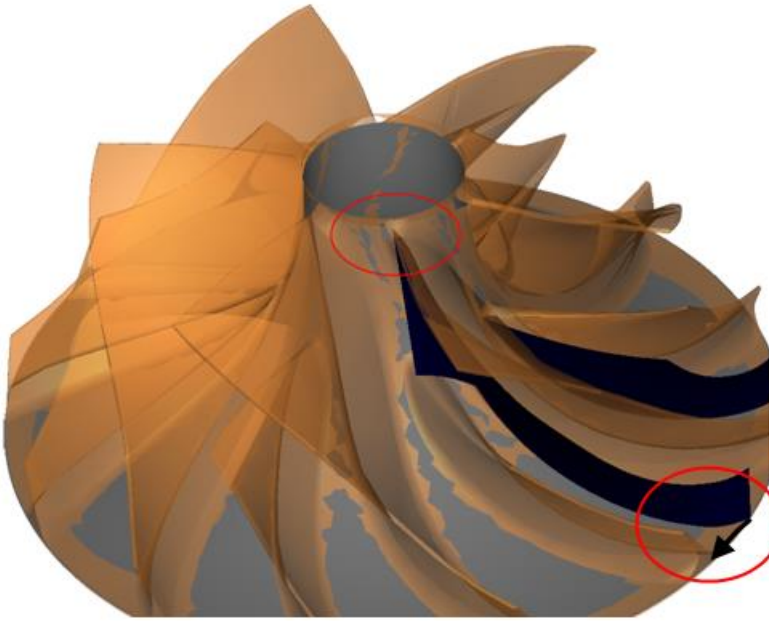
2.4 Mean lines

2.4.1 Mean lines of the main blades

In the initial design mean lines can be also generated based on the default design of CFturbo. To this end the dialog "Design blade mean lines" should be opened and ended per OK. The herewith produced mean surface is now discernable. It will not lie in the center of the blade of the reference impeller geometry initially, which will make a rotation to the right position necessary (Figure 4). In case the toolbox (Import) for setting the position of imported geometries is not visible, it can be opened by right-clicking on the name of the imported impeller (model tree, branch "Imports") and choosing "Set position" in the appearing context menu. Advantageous is a rotation that brings the first point of the hub mean line (i.e., the point at the leading edge) on the center of a blade of the imported impeller (Figure 17).

If, as described in the preceding chapter, extracted m-t-data and β-t-data for the different spans or sections are existent in the form of text files, these should be loaded per "Load extra polyline" into the appropriate diagrams. Subsequently the Bézier curves must be adjusted in a way that they are approximately congruent with loaded m-t-lines. The procedure is like the design of the meridional contour, Figure 8...Figure 13. If extracted blade angles exist, the appropriate values of leading and trailing edge should be typed in the design dialog "Blade properties" (Figure 16).

In case m-t-data are not given, the tangential position of the points of the leading edge at the other sections - the leading edge of the hub section has already been adapted by the rotation of the imported geometry - must be adjusted to the reference geometry. This is to be done by the specification of the angle ϕ0. If a linear distribution of the angles at the mean lines of the leading edge is too much of a constraint, it should be switched to "User defined". Then the angle of every mean line is adjustable individually.



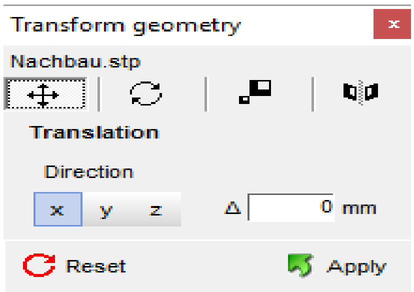


Figure 17 **Figure 18**

After setting the tangential position of the leading edge, the trailing edge can be placed. This is to be done by an iterative change of the wrap angle Δϕ in the dialog "Design blade mean lines". With more than 2 mean lines all angles Δϕ should be coupled linearly. If in the further design this turns out to be a restriction, then the option "Coupled linear" must be deactivated, such that the adjustment of every angle is possible (Figure 18).

Again, every change in the design step "Mean lines" must be checked in the 3D-Preview.

The blade angles at leading and trailing edge will only then fit with those of the imported impeller if correct m-t-data have been used for the design of the mean lines. The same applies for the distribution of the blade angles along the mean lines. In case these data were not available the blade angles at leading and trailing edge must be set in the design step "Blade properties" (Figure 16). When these are adjusted and subsequently checked in the 3D-view, then the blade angle distribution must be corrected in the dialog of the design step "Design blade mean lines". For that purpose, the inner Bézier points of the mean lines must be shifted in an appropriate way.

Probably the correction of the blade angles at leading and trailing edge as well as the correction of the distribution of the lade angles must be performed alternately. Also, it might be that the position of leading and trailing edge at the mean lines must be adjusted again.

2.4.2 Mean lines of the splitter blades

The standard during the design of splitter blades is to treat them like cut-off copies of the main blades (Figure 15). If this option was chosen, a separate design is not possible. If in the further design process, it turns out that the splitter blades cannot be composed in the standard way, the option "Splitter blade linked to main blade" must be deactivated. Adjacently the design of the mean surface of the splitter blades must be carried out in the same way as for the main blades (design step "Design blade mean lines", second tab), see preceding chapter.

3 Blade profiles

3.1 Blade thickness

If the blade thickness is known at leading and trailing edge as well as at the top edge of the blade (i.e. at the shroud) and if the thickness is constant along these edges, then the blade thickness design at the top edge is finished with an exact as possible input of the blade thickness (Figure 15).

Generally, the blade will be thicker at the blade root as at the top edge and will not have a symmetric thickness distribution at pressure and suction side measured at mean line. Beyond it the blade will be cambered stronger at the leading edge as in the vicinity of the trailing edge. Therefore, the following adjustments should be carried out in the design step "Blade profiles":

- Design mode: Freeform (thickness distribution via Bézier curve)
- Increase of the number of the Bézier points (e.g. to 4)
- If necessary, invalidation of the symmetry of pressure and suction side (SS-PS-Coupling: None)

In case it is not feasible to design the blade with the default number of Bézier points, further Bézier points can be added by right-clicking at the Bézier curve (Figure 20). This might be necessary especially at the blade's nose if this is strongly shaped.

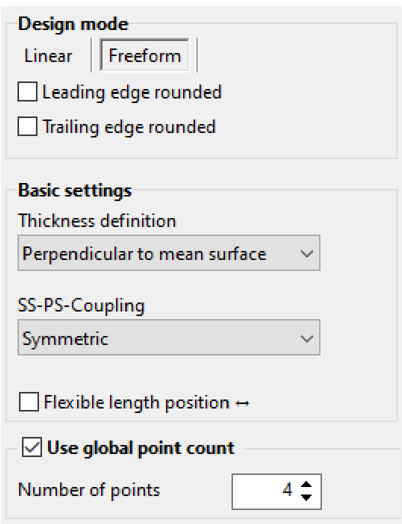


Figure 19

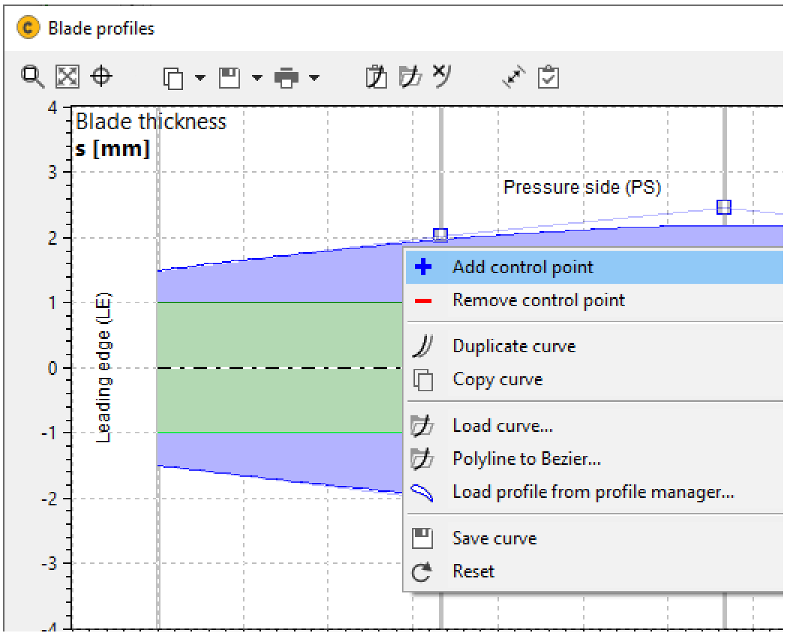


Figure 20

If Bézier points, whose position is to be changed with the help of the mouse, lay on each other, then a toolbox appears, in which one can choose the eligible Bézier point. Beyond it Bézier points can also by adjusted by the direct input of their coordinates. Thereto the appropriate edit box must be opened with a right-click at the Bézier point.

Ideally the Bézier curve must be approximated to a loaded polyline as shown in design of the meridional contour. This polyline must have x-y-pairs that hold a non-dimensional blade length (at the appropriate section, i.e. hub or shroud) and an associated blade thickness that has to be added to the mean surface. If these data are not available, the values of the blade thickness of main and splitter blades must be adjusted in the given way. The check of these adjustments must be done in the 3D-Preview.

3.2 Round leading edge

In the design step "Blade edges" three different modes are provided: "Simple", "Ellipse" und "Bézier". The last option again gives so most comprehensive opportunities for the design and should be chosen, unless leading and trailing edges shall be trimmed. The adaption of the Bézier curve with the help of the movement of the Bézier points has again to be checked visually in the 3D-Preview.

3.3 CFD-Extension

If the design shall be used together with some of CFturbo's CFD-interfaces later, a small outlet extension should be defined, since this will be used for generation of the rotor-stator-interfaces. It is sufficient to check the appropriate checkbox to this end. The size of the extension will be determined with the help of the size of the impeller (Figure 21).

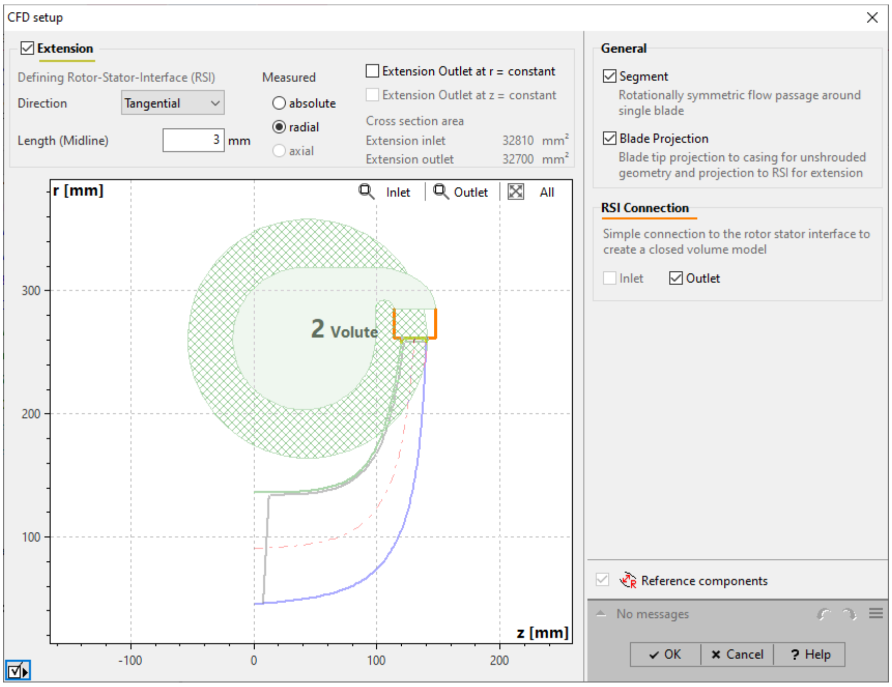


Figure 21

4 Radial diffuser

If a radial diffuser is part of the compressor stage, then inlet and outlet diameter as well as width must be determined and the meridional contour. To this end the same design steps must be carried out as described in chapter 1.2 and 2.2.

5 Volute

It is recommended to load separate parts of the reference geometry of the volute in accordance to the respective design step as separate comparing parts into CFturbo. Herewith a visual comparison in every design step is possible, without interference of parts that are currently not of interest. For the generation of these individual parts, i.e. vaneless radial diffuser and pinch type diffuser, spiral and outlet diffuser, see chapter 2.1.

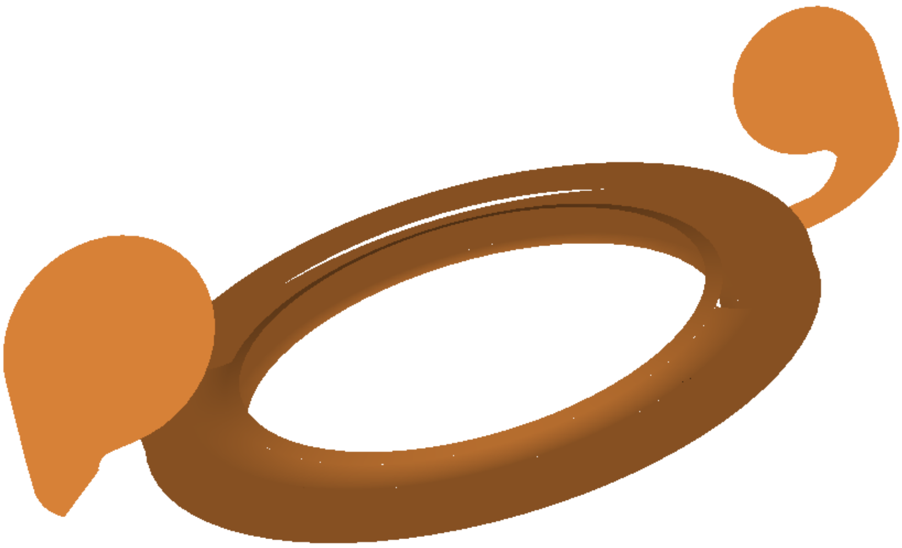


Figure 22

Exemplary two coaxial sections of the spiral as well as the contour of the radial diffuser are displayed in Figure 22.

5.1 Inlet definition

As a starting point in any case the model of the previously designed impeller should be used. For adding a volute component to the impeller, the plus icon at the outlet of the impeller can be pushed followed by the usage of the menu item "Add new volute" (Figure 23). The result is the open design step for the definition of the inlet geometry of the volute, (Figure 24).

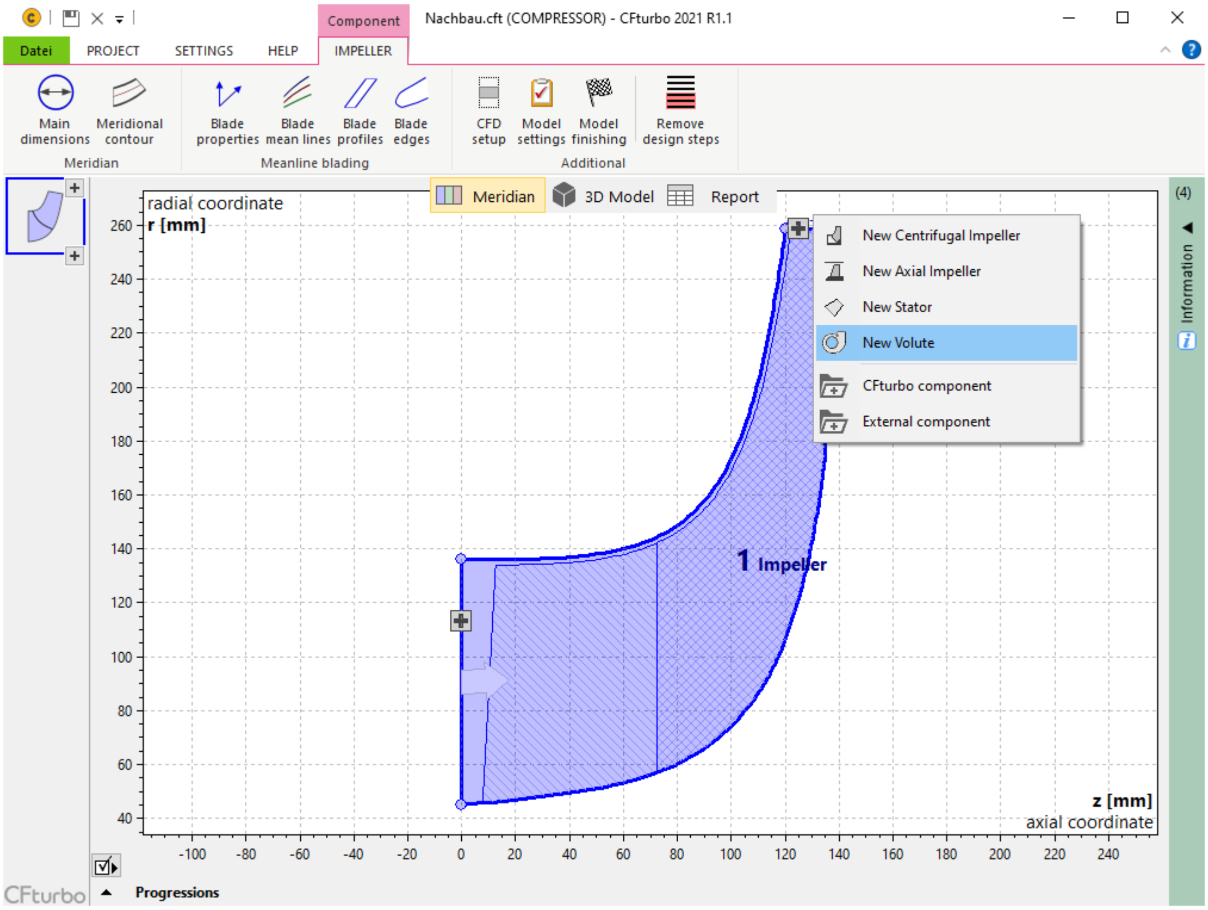


Figure 23

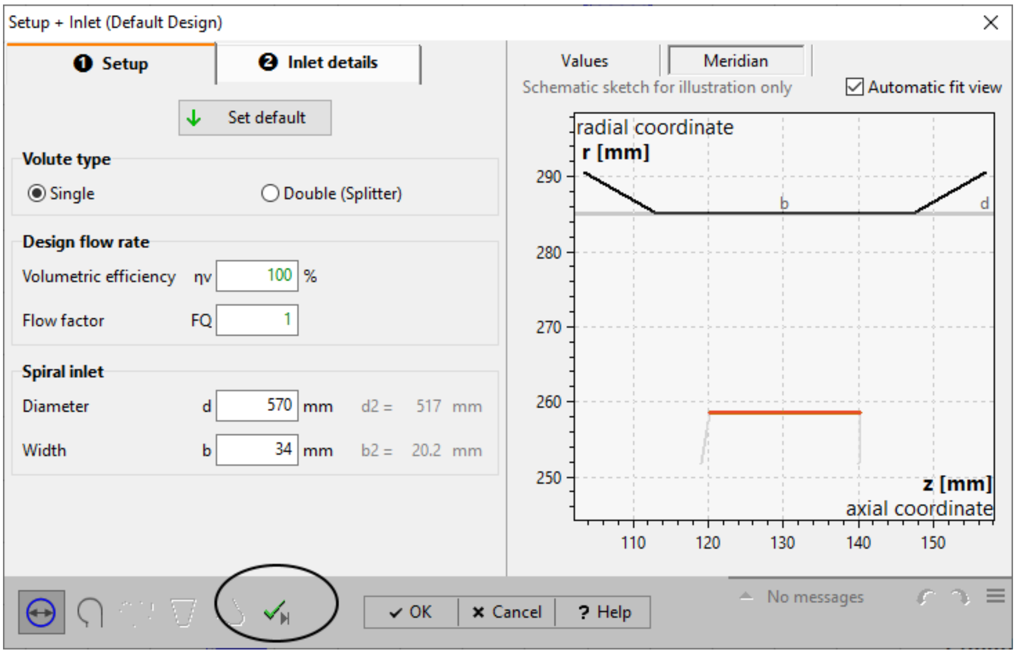


Figure 24

Via "OK + Complete all design steps" now an initial design of the volute can be carried out, that is of course to be modified afterwards.

In the second tab Volute the inlet values of the spiral geometry must be set. These are the inlet diameter d_{In} and the inlet width b_{In}.

After the finishing of the first design step "Setup & Inlet" a 3D-geometry will not yet being produced, which means that a visual comparison with reference geometry is not yet possible. Therefore, in the further design process of the volute it might be necessary to come back to the diffuser design, to do some modifications of the geometric parameters.

5.2 Cross section shape

In the design step "Cross section" the cross-section design of the Spiral is to be chosen. Afterwards the principle cross section shape will be displayed, where a radial extension is assumed (for radial scaling use arrows right above the diagram). When the appropriate cross section shape was chosen, some geometric parameters are editable.

For instance, the choosing of a round asymmetric shape yields the opportunity to design spirals that have an internal location, which means they are bended towards the axis. These shapes are utilized for turbo charger compressors. There are more design options concerning the shape of the inner and outer bend as well as the geometric parameter "Neck width" (side distance from volute inlet to actual volute cross sections) and "Ratio" (semi axis ratio for quarter bend).

The change of these parameters will not be visible in volute design at once, since only after finishing the next design step "Spiral development areas" the 3D-geometry will be discernable. The following applies again: in the further design parameters must be adjusted to the desired geometry.

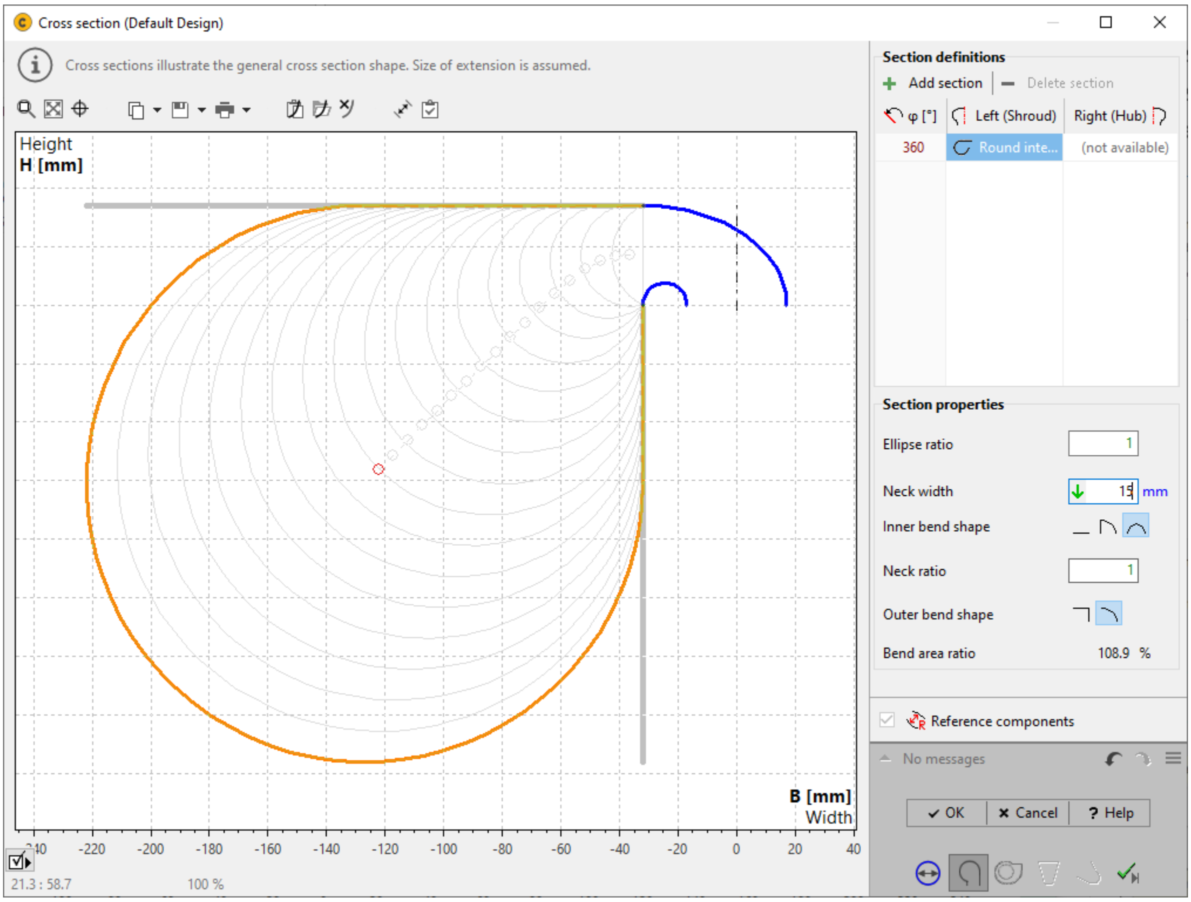


Figure 25

5.3 Spiral geometry

In the design step "Spiral development areas" the actual spiral geometry will be set up and calculated respectively. Here important parameters are radii, heights, widths a. s. o. If a nonlinear distribution of radii or cross section areas along the perimeter of the spiral is necessary, it can be set with the help of the progression diagram at the top.

In case of asymmetric internal volutes (see chapter 5.2) the outer radius r_5, the biggest radial dimension, will be determined with the inlet width of the spiral:

$$r_5 = \frac{d_{In}}{2} + b_{In}.$$

Also, the following relations applies:

$$r_5 = r_4 + H.$$

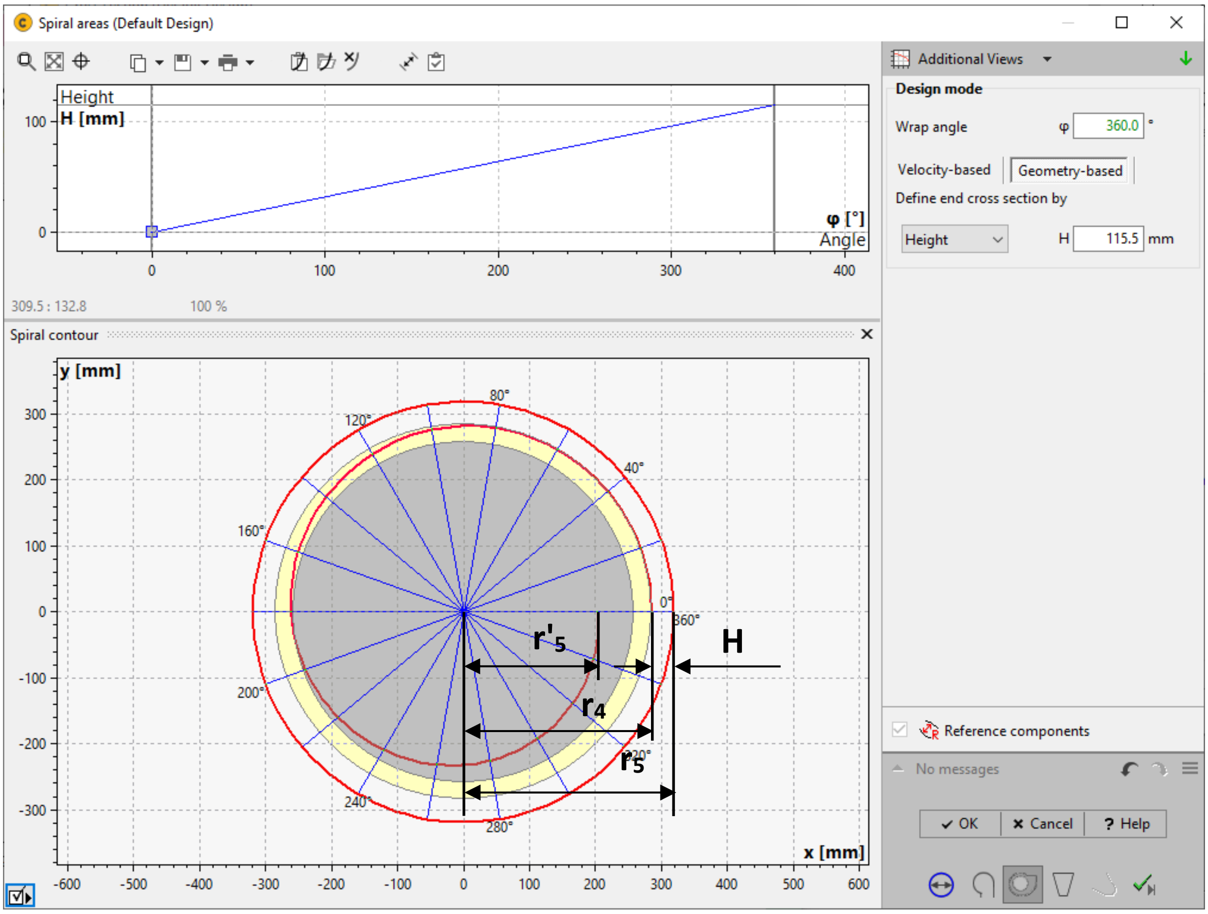


Figure 26

In case of internal asymmetric spirals, the height in the diagram of the height progression (Figure 26) is in accordance to the radius that is made by the inner side of the spiral with the z-axis at the smallest wrap angle (Figure 26). At the location of the biggest wrap angle, the round cross section of the spiral has a diameter of $d_5 = r_5 - r'_5$.

Again, the check of the parameter change, and the altered geometry should be done by the visual comparison with the reference geometry in the 3D-Preview.

5.4 Outlet diffuser geometry

Here the content is the design of the diffuser at the outlet of the spiral ("Diffuser geometry"). The shape ("Direction") of the diffuser is to be chosen and dependent on this shape some geometric parameters must be given. It is recommended to import a reference geometry of the diffuser to check the influence of the parameter changes in the 3D-Preview again.

5.5 Cutwater geometry

Within the last design step, the cutwater must be done in accordance with the reference geometry. Key parameters that must be adjusted are the angular position of the cutwater as well as the form of the cutwater. To this end it can be chosen from two modes. Those are "Simple" and "Fillet".

6 Summary

The redesign of impellers with CFturbo works best in case 2D-data are available, that can be loaded directly into the respective design step where they can be used as a basis for the fitting of the Bézier curves. Currently these 2D-data must be generated outside CFturbo, see e.g. chapter 2.2.

The checking of the geometric design must be carried out in the 3D-Preview visually in every design step.

The blade shaping is currently performed in CFturbo on two spans, which are hub and shroud. If free form 3D blades shall be redesigned, this might not give enough freedom for the design. For milled compressor impellers probably the switch to the option "ruled surface" (Figure 15) is an opportunity to match the given reference geometry in the design process.

Bézier curves that are used in CFturbo for the design are often limited with respect to their degree. This can be possibly not enough to match highly curved geometries.

The outer and inner bend at the transition from the radial diffuser to the spiral (Figure 25) is currently made of the section of an ellipsis. Again, this is possibly not sufficient for all shapes of bends, to match the reference geometry exactly.