Two Dimensional Design of Axial Compressor
An Enhanced Version of LUAX-C

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Thesis for the Degree of Master of Science

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ABSTRACT

The main scope of this thesis is to have a strong tool for a preliminar design and sizing of an axial compressor in a bi-dimensional way, this means that all the parameters are referred to the hub, to the midspan and to the tip of the blade.

This goal has been reached improving a pre existent Matlab^{TM} code based on a monodimensional design.

The developed code, using different *swirl law,* allow to understand the behaviour of the flow in both the axial and radial direction of the compressor, furthermore it plot the blade shape, once at the midspan of each stages, so the rotor and the stator are plot togheter, once for each blade separately, at the hub, at the mid-span and at tip, to show how the blade has to be made to properly follow the flow.

This code has to be intended as an approach point for a more accurate design for axial compressor, e.g. CFD, that always need a good one and bi-dimensional preliminary design to obtain correct results; or it could be used in academic field for a better comprehension from the student of the phenomenas that take place in this kind of machine.

ACKNOWLEDGMENT

First of all I want to thanks Professor Magnus Genrup to give me this big opportunity to develop a work in a really important and prospectfull field such as turbomachinery, and to allow me to add an international experience to my studies.

Also I want to thanks the PhD students of the division of Thermal Power Engineering, department of Energy Science at Lund University that are interested about my work, resolving my doubts; all of this without forget Maura, whose presence permit me to feel less the lack of my city and friend.

At last, but not the least, I want really to thanks a lot my mum and dad, without their support and approval during the years, and their continuos encouragement, all of this could not be possible.

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CHAPTER 1 MAIN CHARACTERISTICS

In everyday life compressors are becoming more and more fundamental, from the production of energy to the transport field, they assumed a strong role for enhance the human condition.
Their operating principle were established more than sixty years ago, and during the last decades all the efforts have been concentrated on how to improve and develop better machine, and on the study of the behaviour of the elaborated flow.

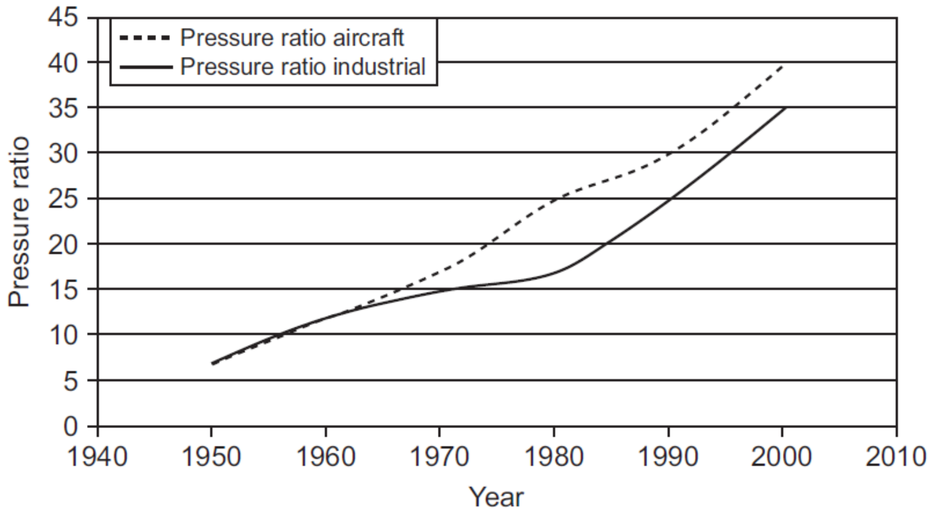


Figure 1-1 Pressure ratio increase along the years

Dynamic compressors are divided in two big family, axial compressor and radial compressor, the choice between them it's the consequence of the valuation of multiple parameters, and it will be work of the designer to find the correct one.

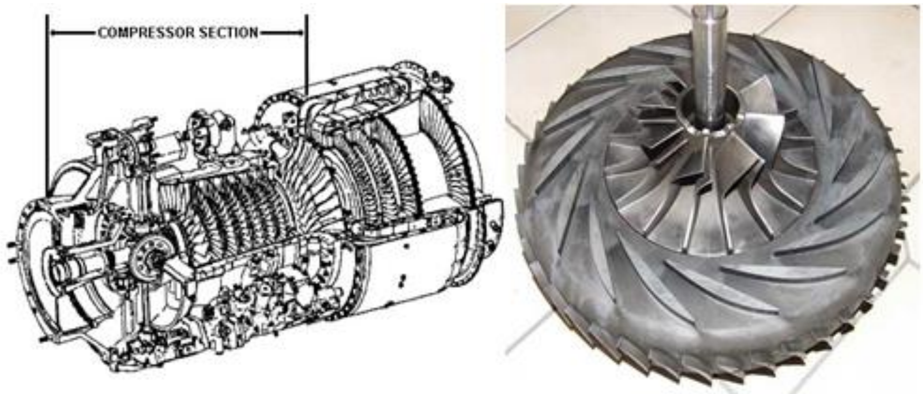


Figure 1-2 Axial and Radial compressor

Axial compressor can elaborate a higher flow than the radial, which has a higher pressure ratio per stage, this means that for the same flow rate the firsts will have a smaller diameter, but it will need more stages to reaches the same pressure ratio.

Another aspect to consider is the efficiency, which reaches better values in the axial one, because the flow withstand less changes of direction along the stages, with minor perturbation through each blade row.

For the same mass flow and pressure ratio radial compressor are cheaper than the other, furthermore they are more resistant in case of damage caused by external object.

In figure 1.2 is it possible to see the behaviour of both compressors in relation to velocity and pressure ratio, is it clear that radial compressors have more margin to the surge, and axial compressor should be used only at high speed.

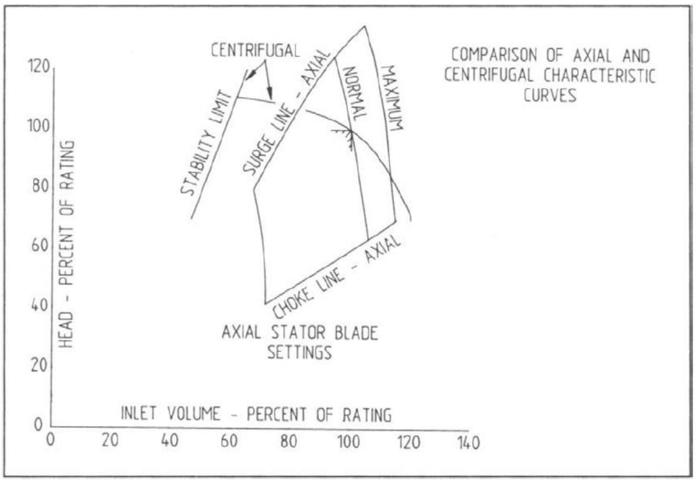


Figure 1-3 Comparison of axial centrifugal characteristic curves (Dresser-Rand)

The main character of this thesis is the axial compressor, which is become the main choose for the most of the application from gas turbine for electric energy production, because of the growth of turbogas plant, to engine for aircraft.

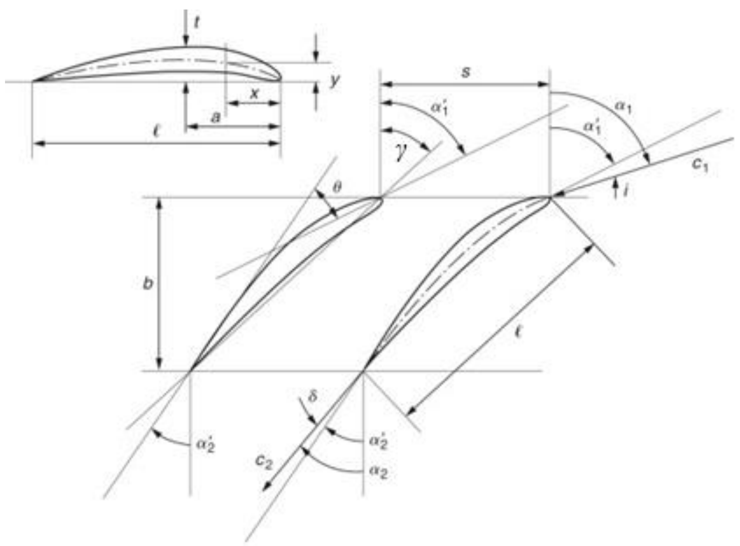
The increase of efficiency in gas turbine has been obtained from the increase in pressure ratio in the compressor and the increase in firing temperature in the combustion chamber; in the axial compressor the total pressure ratio is due to the sum of the increase obtained in each stage, which is limited to avoid high diffusion.

1.1 BLADE NOMENCLATURE

Generally an axial compressor is compose by a variable number of stages where each follow one other, a single stage is made up by a rotor and a stator; both of them present blades disposed in a row, called cascade.

A blade has a curved shape, convex on one side, called suction side, and concave on the other, called pressure side, the symmetric line of the blade is the *camber line*, whereas the line which connect directly the leading and trailing edge is the *chordline*, the distance between these two line is the camber of the blade.

The turning angle of the camberline is called *camber angle*, ϑ, and the angle between the chordline and the axial direction is the *stagger angle*, γ (Figure 1-4).



- *thickness of the blade, t*
- *flow angle,* α
- *blade angle,* α'
- *staggered spacing, s*
- *incidence,* $i=\alpha_1- \alpha'_1$
- *deviation,* $\delta= \alpha_2- \alpha'_2$
- *camber angle,* $\vartheta= \alpha'_1-\alpha'_2$

Figure 1-4 Blade nomenclature

Only at ideal condition the incidence angle will be equal to zero, but for common operational condition it often has different values that could be negative or positive.

The deviation is always greater than zero, because the flow is not able to follow precisely the shape of the blade due to its inertia.

The difference between the inlet flow angle and the outlet one, is called *deflection*, ε, this changing in the flow direction is the real responsible of the change in momentum.

The thickness distribution depends from the blade type, a common kind of profile is the NACA-65 series cascade profile, in this thesis a double circular arc has been adopted for the airfoil.

1.2 LIFT AND DRAG

The reaction forces which the blade exert on the flow are called *drag and lift*, the first act in the same direction of the stream, the second is perpendicular, it arise because the speed of the flow on the suction surface in greater than the flow on the pressure surface, thus, by the Bernoulli equation, the pressure on the under surface is bigger than the one of the upper side of the blade (Figure 1-5).

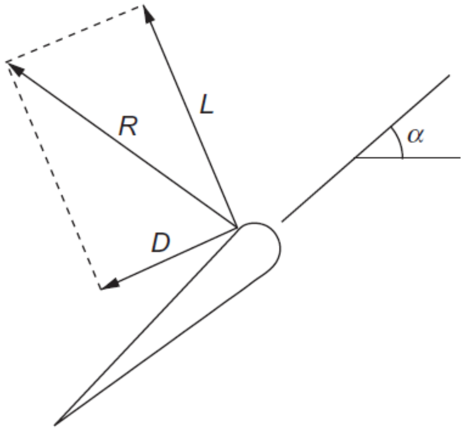


Figure 1-5 Drag and Lift forces

In order to calculate these two forces, the following relations can be used:

$$D = C_D A \rho \frac{c^2}{2} \tag{1.1}$$

$$L = C_L A \rho \frac{c^2}{2} \tag{1.2}$$

Where A is the obstruction of the blade in the flow direction, ρ is the density, c is the velocity of the flow, and C_D and C_L are respectively the coefficient of drag and the coefficient of lift, calculated from experimental dates.

Those two coefficients are strongly influenced by the attack angle, α, in particular, the lift coefficient after a certain values of the incidence goes to zero, this means that stall happen on the blade and it stop to interact with the fluid (Figure 1-6). In a compressor, this entails a drop in the pressure increase and a reduction in all its performance.

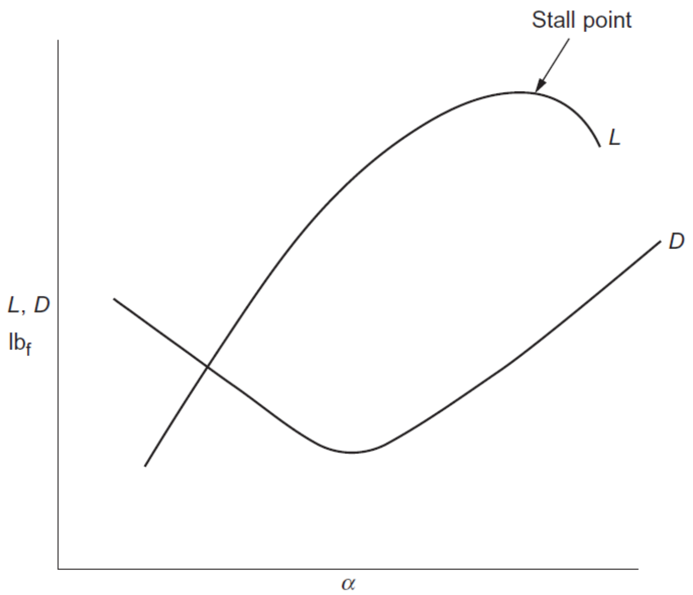


Figure 1-6 Lift and Drag coefficient

1.3 STALL AND SURGE

A compressor has more criticality than a turbine, this, basically, because the flow is forced to move from a zone with low pressure in another at high pressure, that is an unnatural behaviour.

At low blade speed, *rotating stall* may occur, this phenomena belong to the progressive stall family; the blade stall each separately from the others, and this stall patch moves in the opposite direction of the rotation of the shaft. This happen because the patch reduces the available section for the flow to pass between two adjacent blades, so it is deflected on both sides of the cascade (Figure 1-7).

This implies that the incidence of the flow on the left side is increased and the incidence of the flow on the right side is reduced; the frequency with which the stall interests each blade can be near to the natural frequency of blade vibration causing its failure.

Progressive stall is typical of the transitory, but it can be controlled by bleeding the flow from the intermediate stages or using blade with variable geometry, inlet guide vanes (IGV), or both of them.

The most dangerous and disruptive phenomena in compressor is the *surge,* it is the lower limit of stable operation, it occurs when the slope of the pressure ratio versus mass flow curve reaches zero.

When the inlet flow is reduced, the output pressure reaches its maximum, if the flow is reduced more, the pressure developed by the compressor became lower than the pressure in the discharge line, and the flow start to move in the opposite way.

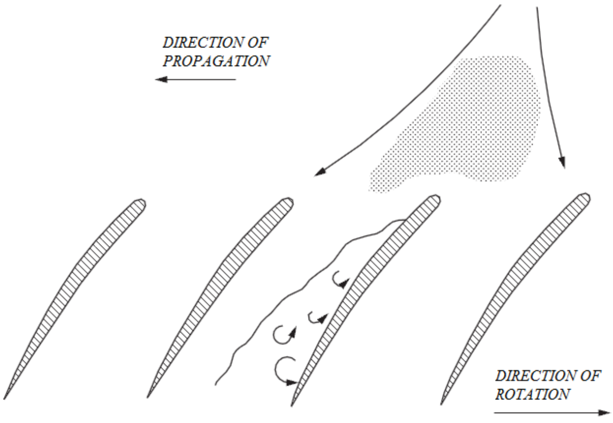


Figure 1-7 Rotating stall

The pressure at the outlet is reduced by the reverse of the flow, thus normal compression start again; since no change in the compressor operation is done, the entire cycle is repeated. The frequency of this phenomenon can be the same of the natural frequency of the components of the compressor, causing serious damage, especially to blades and seals.

Surge is linked with increase in noise level and vibration, axial shaft position change, pressure fluctuation, discharge temperature excursions.

Stall and surge should not be confused even if the past happened, surge must be total avoid, but a multi-stage compressor may operate stably even if one or more stages stalled, treating the compressor casing may avoid this last phenomenon.

Another operating limit of the compressor is *choking*, it happen when the flow in the blades throat reaches a Mach number of 1.0, in this case the slope of pressure ratio versus mass flow curve coming on infinite, thus the elaborated mass flow cannot be increased more.

1.4 TIP CLEARANCE

To avoid rubbing between the rotor and its surrounding casing during rotation, there must be a small clearance, this, linked with the pressure difference across the blade, create a tip clearance flow through this tiny space, forming a tip leakage vortex (Figure 1-8).

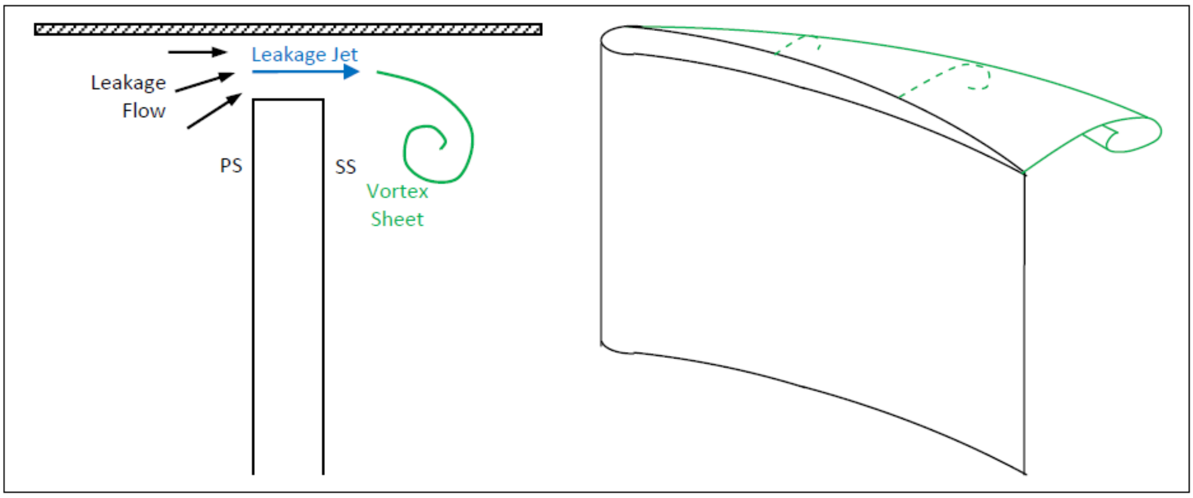


Figure 1-8 Tip clearance flow **(Berdanier)**

In the last stages of the compressor, in order to reach the desired total pressure ratio and to properly follow the flow, the annulus height is really small, so the hub to tip ratio increase, it means that the blade become shorter, thus the percentage of the tip clearance on the total height of the blade increase; this affected stall margin, pressure rise and efficiency.

In general, for one percent increase in clearance-to-span ratio, there is a one to two percent decrease in the efficiency, two to four percent decrease in the pressure rise, and three to six percent decrease in stall margin (Chen, 1991).

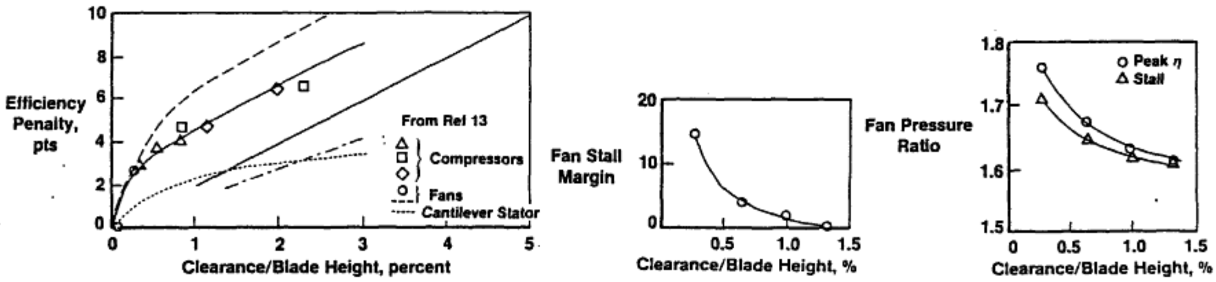


Figure 1-9 Effects of the increased clearance on the performance **(Wisler, 1985)**

CHAPTER 2 THEORY & MODELS

In this chapter it will be presented a review of the modelling concerned turbomachinery, starting from Euler work equation until CFD model, passing throughout bi-dimensional and three-dimensional flow.

2.1 FUNDAMENTAL LAWS

It is possible to write the elementary rate of mass flow like

$$d\dot{m} = \frac{dm}{dt} = \rho c dA_n \tag{2.1}$$

where $dA_n$is the element of area perpendicular to the flow direction, c is the stream velocity and ρ the fluid's density.

In one dimensional steady flow, where we can suppose constant velocity and density, defining two consecutive station, 1 and 2, without accumulation of fluid in the control volume, it is possible to write the *equation of continuity:*

$$\dot{m} = \rho_1 c_1 A_{n1} = \rho_2 c_2 A_{n2} = \rho c A_n \tag{2.2}$$

The fundamental law used in turbomachinery field is the *steady flow energy equation*:

$$\dot{Q} - \dot{W} = \dot{m}\left[(h_2 - h_1) + \frac{1}{2}(c_2^2 - c_1^2) + g(z_2 - z_1)\right] \tag{2.3}$$

but, some observation can be do, first of all flow process in this field are adiabatic, so it is possible to consider $\dot{Q}$ equal to zero, than the quote different $(z_2 - z_1)$ is very small and can be ignored, thus, considering that compressors absorbed energy we can write:

$$\dot{W} = m(h_{02} - h_{01}) \tag{2.4}$$

h_0 is called stagnation enthalpy and is the combination of enthalpy and kinetic energy:

$$h_0 = h + \frac{1}{2}c^2 \tag{2.5}$$

For a compressor the work done by the rotor is

$$\tau\Omega = \dot{m}(U_2 c_{\theta 2} - U_1 c_{\theta 1}) \tag{2.6}$$

where τ is the sum of the moments of the external forces acting on fluid, U is the blade speed and $c_{\theta 2}$ the tangential velocity. So the specific work is

$$\Delta W = \frac{\dot{W}}{\dot{m}} = U_2 c_{\theta 2} - U_1 c_{\theta 1} \tag{2.7}$$

also called *Euler work equation.*

Combining equation (2.4) and (2.7) it is possible to obtain the relation between the two stations, which in our case are the inlet and the outlet of the rotor and the stator:

$$h_2 + \frac{1}{2}c_2^2 - U_2 c_{\theta 2} = h_1 + \frac{1}{2}c_1^2 - U_1 c_{\theta 1} \tag{2.8}$$

those two terms are known as *rothalpy I,* which is constant along a single streamline through the turbomachine; it is also possible to refer it at the relative tangential velocity becoming

$$I = h + \frac{1}{2}(w^2 + U^2 + 2Uw_\theta) - U(w_\theta + U) = h_{0rel} - \frac{1}{2}U^2 \tag{2.9}$$

having define the relative stagnation enthalpy as

$$h_{0rel} = h + \frac{1}{2}w^2 \tag{2.10}$$

In the turbomachinery field is not possible to consider the fluid incompressible anymore, due to the Mach number that is bigger than 0.3; using the local value of this parameter we can relate stagnation and static temperature, pressure and density:

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 \tag{2.11}$$

$$\frac{p_0}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \tag{2.12}$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/(\gamma-1)} \tag{2.13}$$

Combining these three equations and the continuity one, non-dimensional mass flow rate is obtained:

$$\frac{\dot{m}\sqrt{C_p T_0}}{A_n p_0} = \frac{\gamma}{\sqrt{\gamma - 1}} M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{1}{2}\left(\frac{\gamma+1}{\gamma-1}\right)} \tag{2.14}$$

also known as flow capacity.

2.2 DIMENSIONAL ANALYSIS

With this procedure is possible to reproduce physical situation with few dimensionless group, applying it at turbomachines lead first to predict the performance of a prototype from test conducted on a scale model, this is called similitude, and second, to determine the most appropriate kind of machine, for a specified range of speed, flow rate and head, based on the maximum efficiency.

For compressible fluid the performance parameters, which are isentropic stagnation enthalpy change Δh_{0s}, efficiency η and power P can be expressed as function of:

$$\Delta h_{0s}, \eta, P = f(\mu, N, D, \dot{m}, \rho_{01}, a_{01}, \gamma) \tag{2.15}$$

where μ is the viscosity of the fluid, N is the speed of rotation, D the impeller diameter and a_{01} is the stagnation speed of sound at the inlet; selecting N, D and ρ_{01} as common factors it is possible to write the last relationship with five dimensionless groups:

$$\frac{\Delta h_{0s}}{N^2 D^2}, \eta, \frac{P}{\rho_{01} N^3 D^5} = f\left(\frac{\dot{m}}{\rho_{01} N D^3}, \frac{\rho_{01} N D^2}{\mu}, \frac{ND}{a_{01}}, \gamma\right) \tag{2.16}$$

With some passage and considering machine that operate with a single gas and at high Reynolds number it is possible to write it like:

$$\frac{p_{02}}{p_{01}}, \eta, \frac{\Delta T_0}{T_{01}} = f\left(\frac{\dot{m}\sqrt{T_{01}}}{p_{01}}, \frac{N}{\sqrt{T_{01}}}\right) \tag{2.17}$$

it is clear that to fix the operating point of a compressible flow machine, only two variables are required.

The performance parameters are not independent one each others, but with the equation of the isentropic efficiency, we can link them together:

$$\eta_c = \frac{\Delta h_{0s}}{\Delta h_0} = \frac{\left[(p_{02}/p_{01})^{\gamma/(\gamma-1)} - 1\right]}{\Delta T_0 / T_{01}} \tag{2.18}$$

Two of the most important parameters of the compressible flow machine, are *flow coefficient and stage loading*, the first is

$$\phi = \frac{c_m}{U} \tag{2.19}$$

where c_m is the average meridional velocity, and the second is

$$\psi = \frac{\Delta h_0}{U^2} \tag{2.20}$$

both of them can be related to the non-dimensional mass flow $\frac{\dot{m}\sqrt{C_p T_{01}}}{D^2 p_{01}}$ and non-dimensional blade speed $\frac{ND}{\sqrt{\gamma R T_{01}}}$.

Equation (2.17) can be graphically represented in the performance map of high speed compressor (Figure 2-1), surge line is the upper operative limit of any single speed line, above this line aerodynamic instability and stall will occur; the other limit, the lower, is the choke line, this phenomena happen when the flow reaches the velocity of sound, at this point, the mass flow cannot be increase anymore.

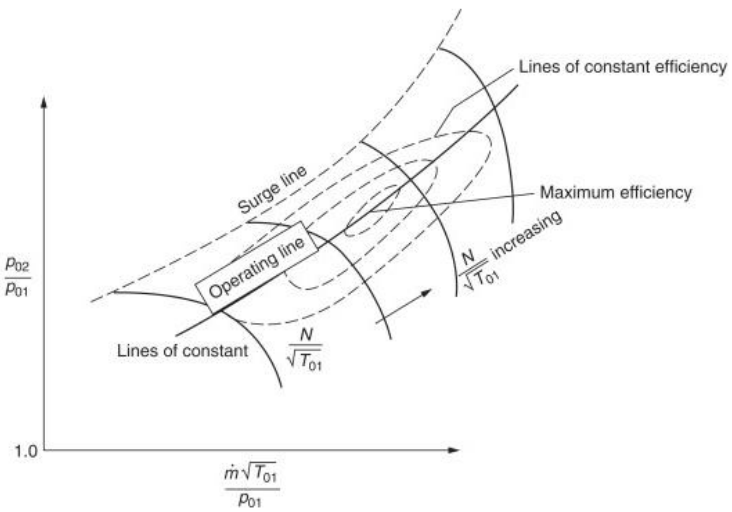


Figure 2-1 Characteristic curves of the compressor **(Johnson & Bullock, 1965)**

For a correct choice of turbomachinery for a given duty, designers use two non-dimensional parameters, *specific diameter* D_s, and *specific speed* N_s; for a compressible fluid machine, find this last parameter allow to determine, for a particular requirement, the better choice between radial and axial flow machine.

$$N_s = \frac{NQ^{1/2}}{(gH)^{3/4}} = N\left(\frac{\dot{m}}{\rho_e}\right)^{1/2}(\Delta h_{0s})^{-3/4} \quad (2.21)$$

2.3 BI-DIMENSIONAL FLOW BEHAVIOUR

It is not possible to consider a monodimensional trend of the stream flow in an axial turbomachinery, because the fluid which passes throughout any blade row will have three components: axial, tangential and radial.

For hub-to-tip ratio more than 4/5 it is possible to assume the radial component equals to zero, but under this limit is not possible to consider anymore streamlines lying on the same radius for the entire machine (Figure 2-2).

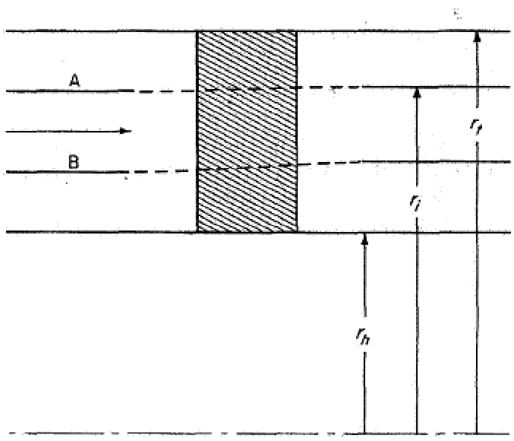


Figure 2-2 Radial shift of streamlines through a blade row **(Johnson & Bullock, 1965)**

Before introduce radial equilibrium theory which rules the three dimensional behaviour we analyse the bidimensional one.

The flow will never follow entirely the blade angle because of its inertia, thus it will leave the trailing edge with a different angle respect to blade exit angle, this means that the boundary layers on the suction and pressure surface growth along the blade and with them the cascade losses (Figure 2-3).

Another cause of the growth of the boundary layers, is the rapid increase in pressure that produce a contraction on the flow, to consider this, a useful parameter it is been introduced, the axial velocity density ratio:

$$AVDR = \frac{\rho_2 c_{x2}}{\rho_1 c_{x1}} = \frac{H_2}{H_1} \tag{2.22}$$

where H is the projected frontal area of the control volume.

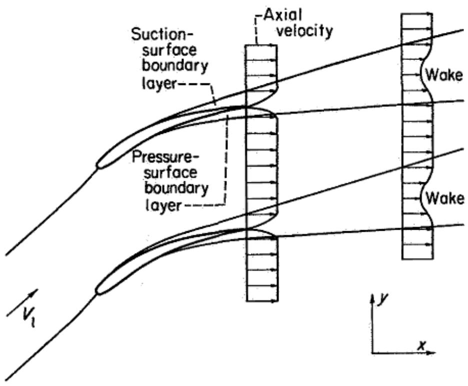


Figure 2-3 Boundary layer **(Johnson & Bullock, 1965)**

Furthermore the increase of the diffusion, which is large in a compressor, tends to produce thick boundary layers and flow separation, specially on the suction surface of the blade, this lead to an alteration of the free stream velocity distribution (Figure 2-4) and loss in total pressure.

To consider this phenomena Lieblein, Schwenk and Broderick developed a parameter, called *diffusion factor,* which is really usefull during the design phase.

$$DF = \left(1 - \frac{c_2}{c_1}\right) + \left(\frac{c_{\theta 1} - c_{\theta 2}}{2c_1}\right)\frac{s}{c} \tag{2.23}$$

when this factor exceeds 0.6 the flow start to separate, so is common to operate with a value of 0.45 in order to prevent losses.

s/c is the pitch chord ratio, also know as the inverse of solidity σ, more used in the U.S., a low values means that across the blade passage is required a lower pressure increase to turn the flow, and the diffusion is restrain, furthermore, with a small value a blade row will have more blade than another with a higher values and the loading will be share better between the blades, but a high values of the chord implies more loss due to the higher wetted area and a longer and more expensive machine; so it is very important to choose an accurate values for the pitch chord ration, because also the shape of the blade, and the interaction between them depends from it, a typicall value for pitch chord ratio is between 0.8 and 1.2.

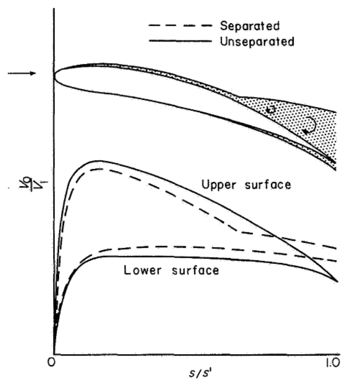


Figure 2-4 Velocity distribution and flow separation **(Johnson & Bullock, 1965)**

To avoid high diffusion, de Haller proposed to control the overall deceleration ratio, both in the rotor and in the stator; the minimum value fixed by him is 0.72 so:

$$dH = \frac{w_2}{w_1} \geq 0.72 \tag{2.24}$$

2.4 EFFICIENCY

In turbomachinery field, the efficiency can be expressed in several ways, the most useful are the isentropic and the polytropic ones.

The first relates the ideal work per unit flow rate per second to the actual work per unit flow rate per second:

$$\eta_{isen} = \frac{h_{02_s} - h_{01}}{h_{02} - h_{01}} \tag{2.25}$$

The real work, represented from the denominator will always be bigger than the ideal work which the compressor needed, due to the energy losses for friction.

Because of the constant pressure lines on an (h,s) diagram will diverge, at the same entropy, the slope of the line representing the higher pressure will be greater; this means that the work supplied in a series of isentropic process, that can be compared to the single stages in an axial compressor, will be more than the isentropic work in the full compression process.

Therefore it is possible to define the efficiency of a compression through a small increment of pressure *dp*:

$$\eta_{poly} = \frac{dh_s}{dh} \tag{2.26}$$

And after several algebraic passages and using Gibbs equation, it is possible to write it like:

$$\eta_{poly} = \frac{R \log\left(\frac{p_2}{p_1}\right)}{\int_1^2 c_p(T) \frac{1}{T} dT} \tag{2.27}$$

If this efficiency is constant across the compressor, then η_{isen} will be lesser, anyway a relationship exist between those two efficiencies (Figure 2-5):

$$\eta_{isen} = \frac{\left(\beta^{(k-1)/k} - 1\right)}{(\beta^{\frac{k-1}{k\eta_{poly}}} - 1)} \tag{2.28}$$

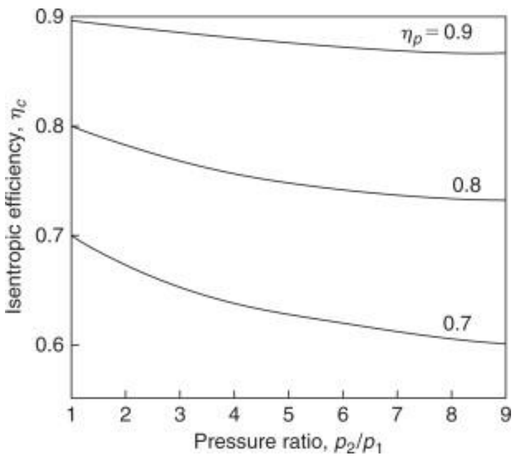


Figure 2-5 Relation between isentropic efficiency , polytropic efficiency and pressure ratio

2.5 VELOCITY DIAGRAMS AND THERMODYNAMICS

For axial machine the relative stagnation enthalpy is constant across the rotor, from equation (2.10) we can write:

$$h_1 + \frac{1}{2}w_1^2 = h_2 + \frac{1}{2}w_2^2 \tag{2.29}$$

for the stator is the same for the stagnation enthalpy:

$$h_2 + \frac{1}{2}c_2^2 = h_3 + \frac{1}{2}c_3^2 \tag{2.30}$$

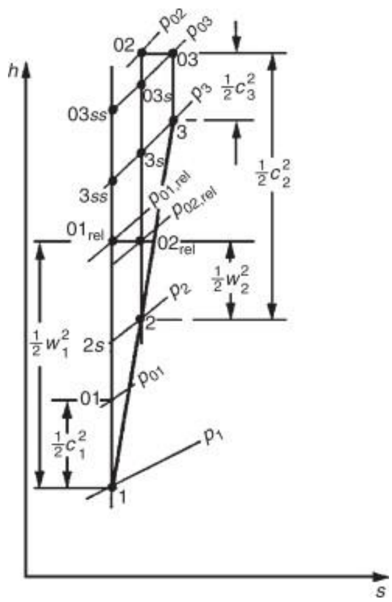


Figure 2-6 Mollier Diagram

For each stage of the compressor, a first approach can be done considering that the direction of the fluid and its absolute velocities are the same at the inlet and the outlet, whereas the relative velocity in the rotor and the absolute one in the stator decrease (Figure 2-7).
In the rotor the flow is turned from β_1 to β_2, after that the stator blades deflected it from α_2 to α_3 which is assumed as equal as α_1.

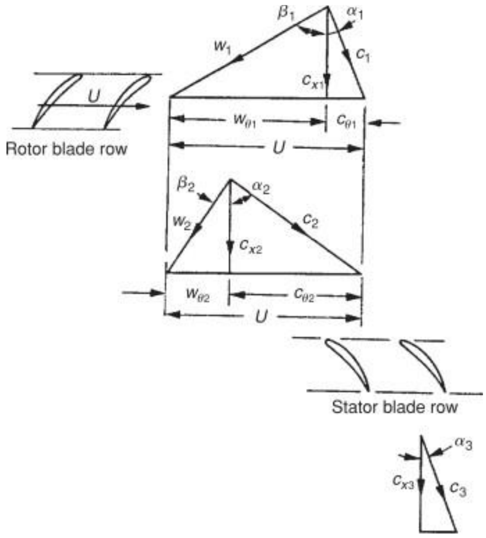


Figure 2-7 Velocity diagram in a compressor stage

Here is possible to define all the component of a two dimensional stream flow:

- c_1 absolute velocity at the rotor's inlet
- w_1 relative velocity at the rotor's inlet
- c_{x1} axial velocity at the rotor's inlet
- $c_{\vartheta 1}$ absolute tangential velocity at the rotor's inlet
- $w_{\vartheta 1}$ relative tangential velocity at the rotor's inlet
- U blade speed
- c_2 absolute velocity at the rotor's outlet
- w_2 relative velocity at the rotor's outlet
- c_{x2} axial velocity at the rotor's outlet
- $c_{\vartheta 2}$ absolute tangential velocity at the rotor's outlet
- $w_{\vartheta 2}$ relative tangential velocity at the rotor's outlet
- c_3 absolute velocity at the stator's outlet
- c_{x3} axial velocity at the rotor's inlet

since we are in a condition of repetitive stage the absolute velocity at the outlet of the stator will be the same at the inlet of the following rotor.

The velocity diagrams are strictly connected to the choice of parameters like reaction, flow coefficient and stage loading, the last one has to be limited in order to prevent flow separation from the blade.

$$\psi = \frac{h_{03} - h_{01}}{U^2} = \frac{\Delta c_\theta}{U} = \frac{c_{\theta 2} - c_{\theta 1}}{U} = \phi(\tan\alpha_2 - \tan\alpha_1) \quad (2.31)$$

but it can also be written like

$$\psi = \phi(\tan\beta_1 - \tan\beta_2) = 1 - \phi(\tan\alpha_1 + \tan\beta_2) \quad (2.32)$$

where (tan β_1-tanβ_2) is the flow turning in the rotor, this means that if the flow coefficient increases, for a fixed stage loading, the required value of that term will be lesser.
As regard the reaction, the connection with the velocity triangles can be written as

$$R = \frac{w_1^2 - w_2^2}{2U(c_{\theta 2} - c_{\theta 1})} = \frac{1}{2}\phi(\tan\beta_1 + \tan\beta_2) \quad (2.33)$$

or

$$R = \frac{1}{2} + (\tan\beta_2 - \tan\alpha_1)\frac{\phi}{2} \quad (2.34)$$

Combining equation (2.31) with (2.33) we obtain:

$$\psi = 2(1 - R - \phi\tan\alpha_1) \quad (2.35)$$

which gives the flow angle for the stator:

$$\tan\alpha_1 = \frac{1 - R - \psi/2}{\phi} \qquad \tan\alpha_2 = \frac{1 - R + \psi/2}{\phi} \quad (2.36)$$

and for the rotor:

$$\tan\beta_1 = -\frac{R+\psi/2}{\phi} \qquad \tan\beta_1 = -\frac{R+\psi/2}{\phi} \tag{2.37}$$

From this it is clear how reaction can influence the fluid outlet angles from each blade row (Figure 2-8):

- If R= 0.5 from the equation (2.33) $\alpha_1=\beta_2$ and the diagram is symmetrical
- If R>0.5 $\alpha_1<\beta_2$ and the diagram is inclined to the right
- If R<0.5 $\alpha_1>\beta_2$ and the diagram is inclined to the left

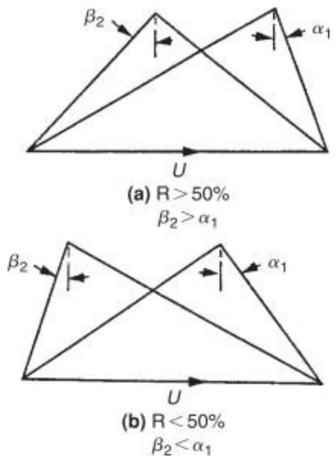


Figure 2-8 Influence of Reaction on Velocity diagram **(Dixon & Hall, 2010)**

2.6 OFF DESIGN PERFORMANCE

Considering equation (2.31), Horlock suggest that the fluid outlet angles does not change for a variation of the inlet angle up to the stall point, so it is possible to write:

$$\psi = 1 - \phi t \tag{2.38}$$

the value of t is given by the values chosen for ψ and Φ.

Test's results from Howell demonstrate that α_1 and β_2 are not constant far from the design point, in figure (Figure 2-9) there is the comparison between the assumption of Horlock and the results obtained by Howell.

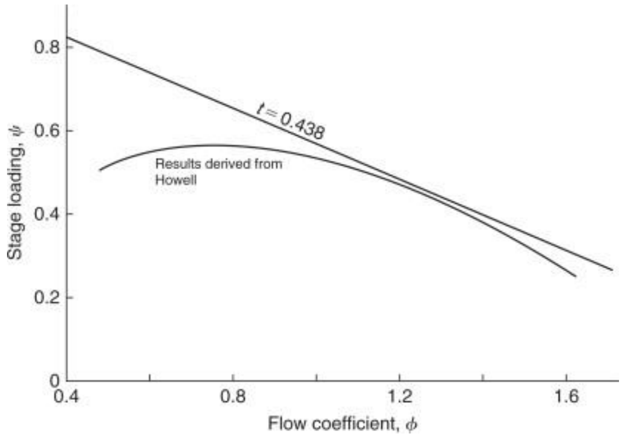


Figure 2-9 Comparison of analysis with result from measure

2.7 THREE DIMENSIONAL FLOW BEAHVIOUR

In order to make an accurate analysis of the flow stream it is essential to introduce the radial component of the velocity, this exist because there is a temporary imbalance between the radial pressure and the centrifugal forces that acted on the flow (Figure 2-10).

The *radial equilibrium theory,* which is used for three-dimensional design, consider the flow outside a blade row in a radial equilibrium, it means that in a generic station sufficiently far from the blade, the stream flow can be considered axisymmetric so all the parameters are the same for each cascade of the same row.

In ϑ direction, forces of inertia and force of pressure does not exist, thus, we can write the equilibrium only for the radial direction:

$$(p+dp)(r+dr)d\vartheta - prd\theta - \left(p + \frac{1}{2}dp\right)drd\theta = \frac{dmc_\theta^2}{r} \tag{2.39}$$

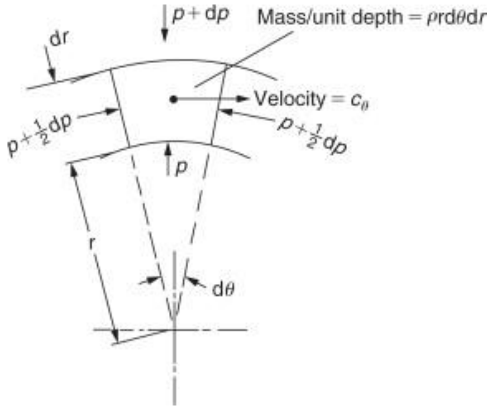


Figure 2-10 Forces acting on a fluid element

The RHS of the equation (2.38) is the force of inertia which is centrifugal, the LHS is the pressure component, ignoring second order's terms or smaller and writing dm=ρrdrdϑ we obtain

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{c_\vartheta^2}{r} \tag{2.40}$$

this is the conservation of momentum in the radial direction.

Knowing c_ϑ^2 and ρ it is possible to obtain the radial pressure variation along the blade:

$$p_{tip} - p_{hub} = \int_{hub}^{tip} \rho c_\vartheta^2 \frac{dr}{r} \tag{2.41}$$

The general form of the radial equilibrium equation for compressible flow may be obtained using also stagnation enthalpy and entropy:

$$\frac{dh_0}{dr} - T\frac{ds}{dr} = c_x\frac{dc_x}{dr} + \frac{c_\vartheta}{r}\frac{d}{dr}(rc_\theta) \tag{2.42}$$

If the terms in the LHS are constant with radius, we have:

$$c_x\frac{dc_x}{dr} = -\frac{c_\vartheta}{r}\frac{d}{dr}(rc_\theta) \tag{2.43}$$

From this equation, choosing a distribution for the tangential velocity it is possible to obtain the axial velocity one, this is very useful for the indirect problem; some of the distributions used for c_ϑ are:

- Forced vortex flow
- Free vortex flow
- Exponential vortex flow
- Constant reaction vortex flow

2.7.1 Forced vortex flow

In this law c_ϑ varies directly with the radius:

$$c_\theta = k_1 r \tag{2.44}$$

It means that the bending moment grew with the radius, so the blade will be high stressed; about the axial velocity at the inlet, from equation (2.43) we obtain

$$c_{x1}^2 = constant - 2k_1^2 r^2 \tag{2.45}$$

The work distribution will not be uniform along the blade:

$$h_{02} - h_{01} = U(c_{\theta 2} - c_{\theta 1}) = \Omega(k_2 - k_1)r^2 \tag{2.46}$$

Combining this with equation (2.41) lead to find the outlet axial velocity:

$$c_{x2}^2 = constant - 2[k_2^2 - \Omega(k_2 - k_1)]r^2 \tag{2.47}$$

It is possible to find the constant from the continuity of mass flow:

$$\dot{m} = \int_{hub}^{tip} c_{x1} \rho 2\pi r dr = \int_{hub}^{tip} c_{x2} \rho 2\pi r dr \tag{2.48}$$

The forced vortex law is much utilized in practise because the difference between inlet and outlet axial velocity for each stage is very low, so the diffusion is restrain and the margin to the stall is remarkable.

The other three laws are obtained from the general whirl distribution, simply choosing different *n* values:

$$c_{\theta 1} = ar^n - \frac{b}{r} \tag{2.49}$$

$$c_{\theta 2} = ar^n + \frac{b}{r} \tag{2.50}$$

where a and b are constants, with this choice the work will always be constant with the radius.

2.7.2 Free Vortex Flow (n=-1)

In this case $c_{\theta 1}$decrease with the radius:

$$c_{\theta} = \frac{k}{r} \tag{2.51}$$

and the angular momentum ($c_{\vartheta}r$) is constant, using equation (2.43) it is clear that c_x will be constant everywhere.

The work distribution is independent from the radius and the tangential forces over the blade decreases with it, but this kind of law will require a highly twisted rotor blade even if conservative dimensionless performance parameters are used (Aungier, 2003).

Another disadvantage is the marked degree of reaction with radius, which become negative near the hub; this means that because of the lower blade speed at the root section, more fluid deflection is required for the same work input, this entail a high diffusion that can lead to stall (Saravanamuttoo, Rogers, Cohen, & Straznicky, 2009).

2.7.3 Exponential Vortex Flow (n=0)

The main advantage to use this design law is the chance to have constant camber stator blade, also with constant stagger angle, with an accurate choice of φ, ψ, at the references radius, this is a good way to reduce manufacturing cost; furthermore, with this design it is possible to obtain the higher hub reaction for any choice of the reference one (Aungier, 2003), and a reduced maximum Mach number for the rotor (Horlock, 1958).

2.7.4 Constant Reaction Vortex Flow (n=1)

This is the type of project law that more than the others let us to get close to the constant reaction, by the way this result will never be achieved, because Φ is not constant across the rotor, and the reaction at the reference radius should be equals to 1.

The main problem of this design is that the axial velocity at the rotor outlet could reach zero near the tip radius, so this zone is a reverse flow zone which is unacceptable, to avoid this Φ at the reference radius must be increased.

This kind of law offers a good margin from stall because the velocity ratios across the blade rows are limited.

2.8 ACTUATOR DISK THEORY

In this theory the blade row, stator or rotor, is replaced by a disc of infinitely small axial thickness with concentrated parameter, across which a rapid and quickly change in vorticity and tangential velocity happen, on the other hand, the axial and radial velocities are continuous. Far upstream (∞1) and far downstream (∞2) from the disk, radial equilibrium exist, but not from the first station to the second one (Figure 2-11).

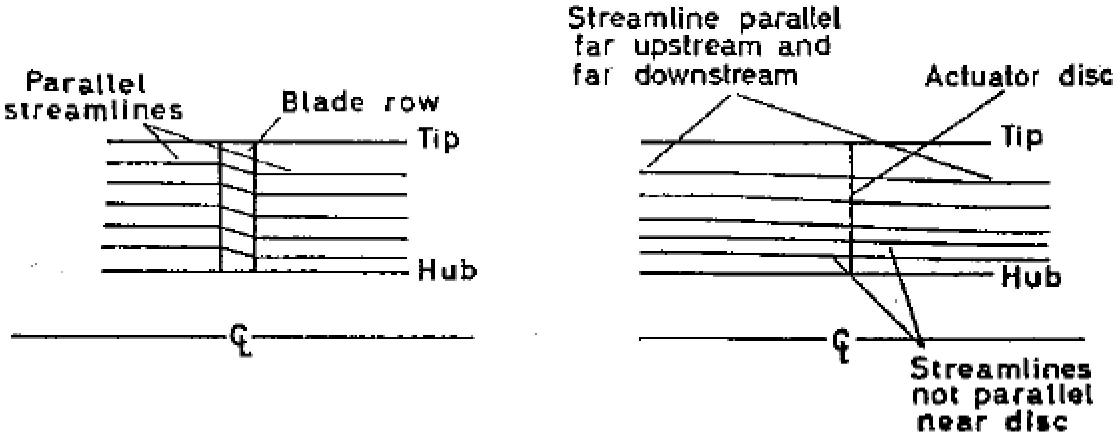


Figure 2-11 Actuator disk theory **(Horlock, 1958)**

This theory proves that at any given radius of the disc, the axial velocity is the same of the mean of the axial velocities far upstream and downstream at the same radius:

$$c_{x01} = c_{x02} = \frac{1}{2}(c_{x\infty1} + c_{x\infty2}) \quad (2.52)$$

this is the mean value rule.

The main result of actuator disk theory is that velocity perturbation, which is the difference in axial velocity between a generic position and the far one, decay exponentially distant from the disk, this decay rate is:

$$\frac{\Delta}{\Delta_0} = 1 - exp\left[\mp\frac{\pi x}{(r_t - r_h)}\right] \quad (2.53)$$

where Δ is the perturbation in a generic point and Δ_0 the one at the disc (Figure 2-12).

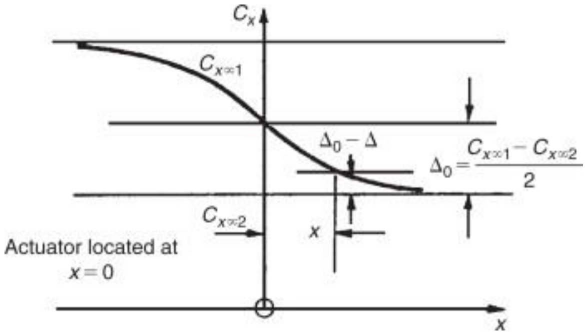


Figure 2-12 Velocity perturbation in the Actuator disk **(Dixon & Hall, 2010)**

Combining equation (2.51) and (2.52) is it possible to find the axial velocity value for a generic position:

$$c_{x1} = c_{x\infty1} - \frac{1}{2}(c_{x\infty1} - c_{x\infty2})exp\left[\frac{\pi x}{(r_t - r_h)}\right] \tag{2.54}$$

$$c_{x2} = c_{x\infty2} + \frac{1}{2}(c_{x\infty1} - c_{x\infty2})exp\left[-\frac{\pi x}{(r_t - r_h)}\right] \tag{2.55}$$

In axial turbomachinery field, where the space between consecutive blade rows is very small implying mutual flow interaction and strong interference effects, this theory is really useful, because this interaction may be calculated simply extending the result obtained from the theory for the isolated disk.

2.9 COMPUTATIONAL FLUID DYNAMICS

Flow behaviour in the compressor is highly three-dimensional, due to low aspect ratio, corner separation, growth of boundary layers, endwall flow, tip clearance flow, hub corner vortex (Figure 2-13), so using actuator disk theory to the design of turbomachinery implies limitation in the final results.

During the past two decades the use of computational fluid dynamics (CFD) in the design of axial compressor has growth, thanks also to the increase of power of the calculators in the last years.

The main purpose of CFD is to solve the systems of equation that describe fluid flow behaviour: conservation of mass, Newton's second law and conservation of energy, for a given set of boundary condition. This system of equation is formed by unsteady Navier-Stokes equations, which are differential equations, and they must be converted in a system of algebraic equation to represent the interdependency of the flow at some point to the nearer ones. The main purpose of CFD is to solve the systems of equation that describe fluid flow behaviour: conservation of mass, Newton's second law and conservation of energy, for a given set of boundary condition. This system of equation is formed by unsteady Navier-Stokes equations, which are differential equations, and they must be converted in a system of algebraic equation to represent the interdependency of the flow at some point to the nearer ones.

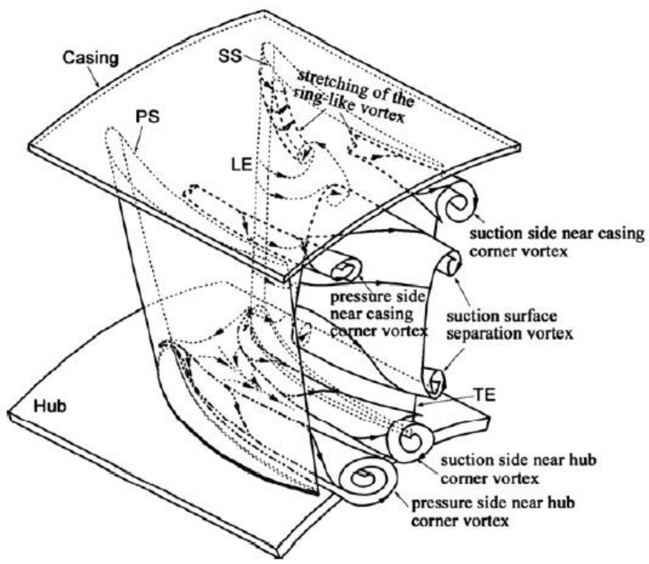


Figure 2-13 3D flow structure **(Xianjun, Zhibo, & Baojie, 2012)**

The points in which the values and the property of the fluid are evaluated, are set and connected together with a numerical grid, also called mesh (Figure 2-14); the accuracy of the numerical approximation strictly depend from the size of the grid, more is dens, better is the approximation of the numerical scheme, however this will increase the computational cost, also in terms of time for the iterations.

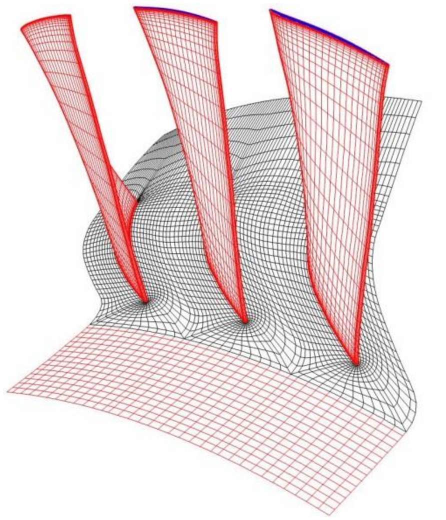


Figure 2-14 Example of mash

In the field of turbomachinery, where the flow is very unsteady, this discretisation besides the space domain must be done also for the time one, to achieve this, the solution procedure is repeated several times at discrete temporal intervals.

The most important step in CFD is defining the boundary condition, it will have a great influence on the quality of solution; at the inlet, flow conditions, total pressure, total temperature and velocity components must be specified .

For the exit boundary conditions the best result are obtained using the static pressure outlet to achieve the required mass flow.

Another type of boundary conditions are defined for the blade surface also considering hub with a rotating wall boundary, and shroud; to simulate repeating blade rows, periodic boundaries should be used for the passage sides of the grid (Figure 2-15).

After that the software has solved the governing equations for the discretised domain, the last step of the process is the analysis of the converged solution.

CFD has to be considered complementary to experimental approach and theoretical one, and not a substitute of them, *one and bi-dimensional preliminary design are still fundamentals to obtain a good result from CFD*, if the result from those design are wrong, it will be impossible to have valid outcome.

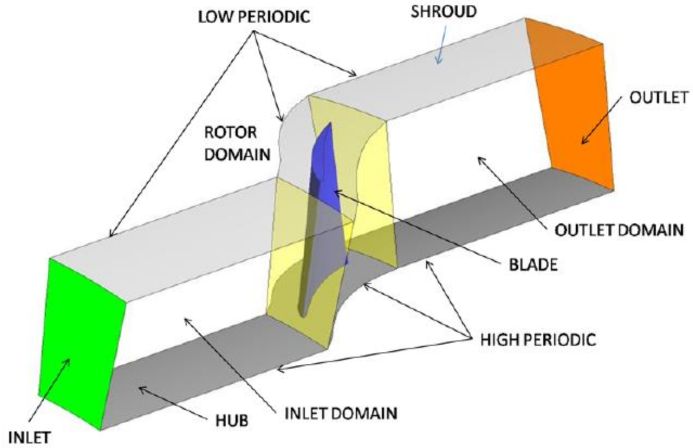


Figure 2-15 Boundary Layer

CHAPTER 3 THEORY USED IN THE CODE

This thesis is based on a previous work made by Niclas Falck called Axial Flow Compressor Mean Line Design, its concern a Matlab code called LUAX-C, which permit to design an axial flow compressor with calculations based on one dimension analysis, so all the parameters are referred to the mean radius.

As regard this thesis work, the scope is to have a more accurate design thanks to bi-dimensional analysis, thus the parameters will vary also in the radial direction of the compressor and not only in the axial one, furthermore a new kind of geometry for the axial machine it is been created, in this geometry the radius behaviour across the compressor is governed by a loop based on the convergence of the outlet total temperature, this give a shape of the machine closer to the reality than the older ones.

One of the most important improvements is the possibility to limit the hub to tip ratio at the last stage of the compressor avoiding in this way the increase of leakage flow.

The variation of the parameters along the radial direction has been obtained using different swirl law such as *Forced Vortex Law* and the *Generic Whirl Distribution*, in this way all the output parameters are referred, in addition to the mid span, also to the hub and to the tip of the blade.

3.1 PREVIOUS WORK

In order to have a better idea of how LUAX-C operate, is suggested to refer to the previous work made by Niclas Falck, here only a review of the principles on which it is based has been done.

There are three main loop, one inside the other, that control all the parameters, the convergence of pressure, reaction and entropy increase iteration, based on the Newton-Rhapson model guarantee the precision of the results (Figure 3-1).

The main specifications necessary to start the calculation for the compressor are several:

- Type of compressor

- Mass flow
- Number of stages
- Pressure ratio
- Rotational speed stage reaction

Some of the parameters specified at the beginning will vary across the compressor, most of them in a linear way:

- Tip clearance, ε/*c*
- Aspect ratio, *h/c*
- Thickness chord ratio, *t/c*
- Axial velocity ratio, *AVR*
- Blockage factor, *BLK*
- Diffusion factor, *DF*

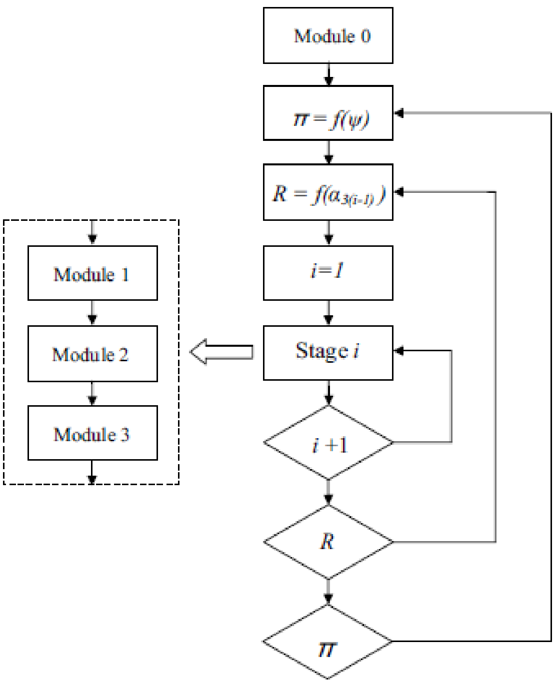


Figure 3-1 Structure of the iterations **(Falck, 2008)**

Only for the stage loading the distribution is a ramp type in which ψ decrease along the stages.

To start the calculation the code also need the inlet specification such as inlet flow angle α, stage flow coefficient and hub tip ratio.

All the parameters referred to the flow like velocities, angles, temperature and so on, are calculated in the inner loop, this happen for each stage, both for the rotor and the stator, when this procedure is finish, the code start to calculate the blade angles.

LUAX-C provides the losses related to the profile of the blade and the end-wall ones, using correlation made by Lieblein, these losses are also expressed in terms of entropy increase; in addition a surge graph is plotted, where is possible to check if surge phenomena subsist and in which stage.

Another very important parameter calculated by this code is the pitch chord ratio, it is possible to choice the method to use between Hearsey, McKenzie and diffusion factor one.

3.2 OUTLET TEMPERATURE LOOP

In order to make the MATLAB code more accessible and easier to handle, improve and understand a separation of the three main loops has been made, after that a new loop, the most external, has been created, it regards the exit temperature from the outlet guide vanes.

Knowing this parameter permit to obtain the root mean square radius (RMS) at the outlet of the compressor, which influence the trend of the mean radius across the machine (Figure 3-3) and limit the hub to tip ratio at the outlet.

To start the iteration a guess value for $T_{0,OGV}$ has been fixed, with this value and the outlet pressure obtained from the pressure ratio, using the *state function* of LUAX-C the static enthalpy at the outlet is found :

$$h_{OGV} = h_{0,OGV} - \left(\frac{c_{m,OGV}}{2}\right)^2 \tag{3.1}$$

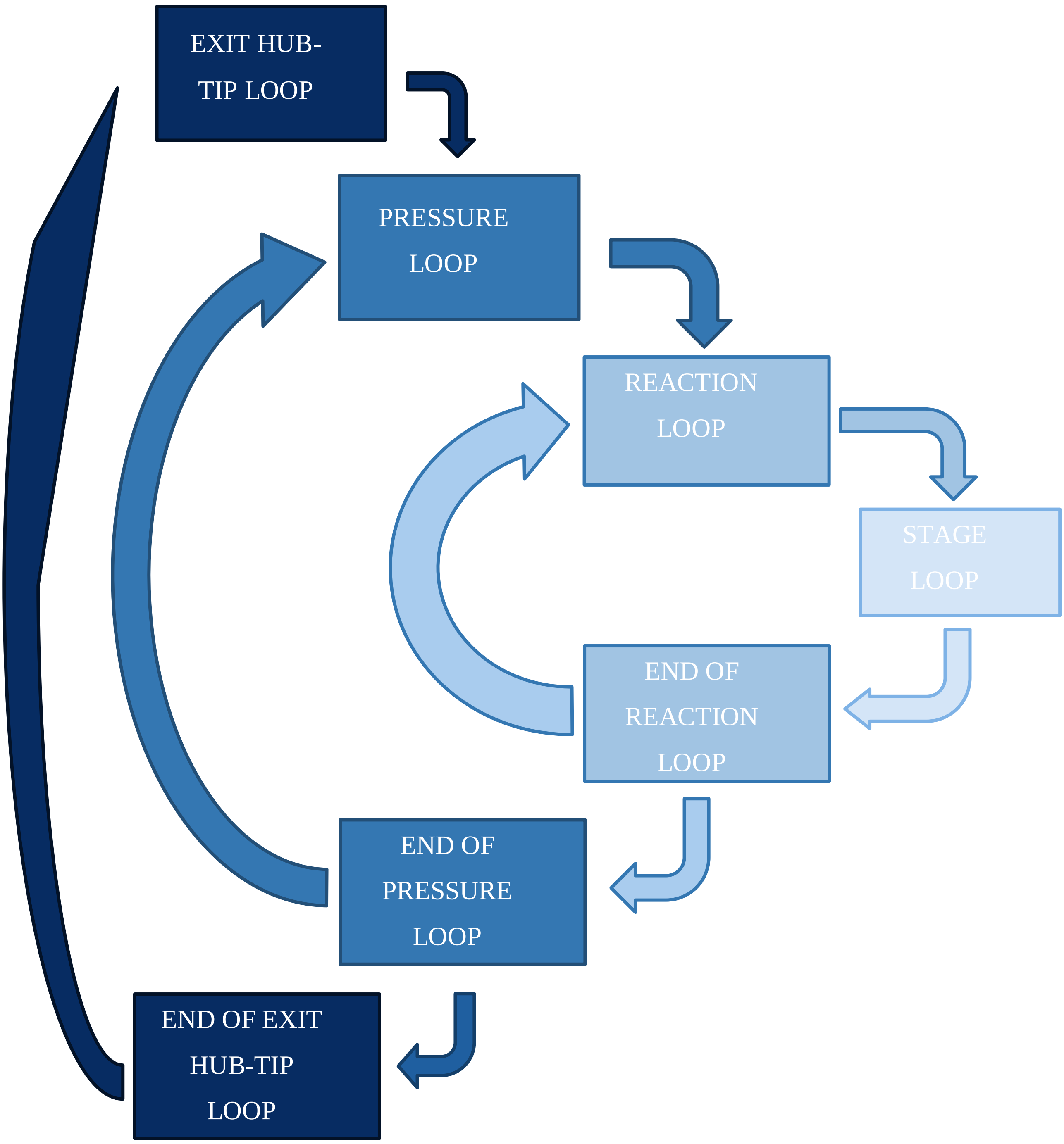


Figure 3-2 LUAX-C loops

Where the axial velocity at the exit of the OGV, $C_{m,OGV}$ is an input value for the first iteration and then is changed with the right values during the loop.

Now using the static enthalpy with the exit entropy in the *state function*, the exit density is obtained, with this last parameter is possible to find the exit RMS:

$$area_{out} = \frac{flow_{Nstg}}{\rho_{OGV} c_{m,OGV}\ BLK_{Nstg}} \quad (3.2)$$

$$area_{eff} = area_{in} - area_{out} \quad (3.3)$$

$$r_{rms,out} = \sqrt{\frac{area_{eff}}{\pi}} \quad (3.4)$$

$C_{m,OGV}$ and $r_{rms,out}$ are used in the stages loop to find the hub and tip radius, and AVR, necessary to consider the decrease of the axial velocity along the compressor.

$$\frac{c_{m,OGV}}{c_{m,in}} = \prod_{i=1}^{N_{stg}} AVR_i \quad (3.5)$$

$$AVR_i = \left(\frac{c_{m,OGV}}{c_{m,in}}\right)^{\frac{1}{2N_{stg}}} \quad (3.6)$$

And for the RMS radius:

$$r_{rms,i} = r_{rms,in} + \left(r_{rms,out} - r_{rms,in}\right)\frac{(i-1)}{\left(N_{stg}-1\right)} \quad (3.7)$$

This value allows to calculate the radius at the top and the bottom of the blade, at the inlet of the rotor it will be:

$$r_{hub,1} = \sqrt{{r_{rms}}^2 - \frac{area1}{2\pi}} \quad (3.8)$$

$$r_{tip,1} = \sqrt{{r_{rms}}^2 + \frac{area1}{2\pi}} \quad (3.9)$$

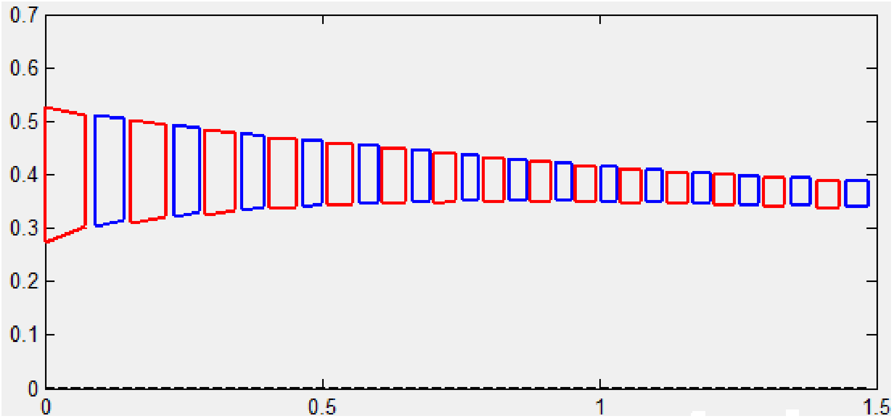


Figure 3-3 flow path behaviour with new design

This kind of design could be obtained selecting *Constant exit hub/tip* in the compressor type label, in the main window of LUAX-C.

3.3 SWIRL LAW

All the variables and parameters in the hub and tip of the blade along the compressor are obtained using different swirl laws, which gives the distribution for the absolute tangential velocity used in the radial equilibrium equation.

3.3.1 Forced vortex law

The forced vortex law used in this thesis derives from a Rolls Royce lecture notes of Cranfield University UK, where a procedure to calculate c_ϑ and c_m is given.
At the rotor inlet the situation is:

$$c_{\theta 1,r} = c_{m1}(m)\mu_1 \tan \alpha_{m1} \tag{3.10}$$

Where c_m(m) is the axial velocity referred to the mean radius and μ is:

$$\mu = \frac{r}{r_m} \tag{3.11}$$

And r can be the radius at the hub or at the tip.
The axial velocity is finding from:

$$c_{m1,r} = c_{m1}(m)\sqrt{1 + 2\tan^2(\alpha_{m1})(1 - {\mu_1}^2)} \tag{3.12}$$

The axial velocity at the hub and the tip is obtained simply choosing the corresponding radius at the numerator of μ.

At the outlet of the rotor, which is also the inlet of the stator the used correlation are:

$$c_{\vartheta 2,r} = c_{m2}(m)\tan(\alpha_{m1})\mu_2 + \frac{\psi}{\phi_2} \tag{3.13}$$

$$c_{m2,r} = c_{m2}(m)\sqrt{1 + 2\tan^2(\alpha_{m1})(1 - {\mu_2}^2) - 4\tan(\alpha_{m1})\frac{\psi}{\phi_2}\log\mu_2} \tag{3.14}$$

To find the velocities at the stator outlet the same equation for the rotor inlet has been used:

$$c_{\theta 3,r} = c_{m3}(m)\mu_3\tan\alpha_{m1} \tag{3.15}$$

$$c_{m1,r} = c_{m3}(m)\sqrt{1 + 2\tan^2(\alpha_{m1})(1 - {\mu_3}^2)} \tag{3.16}$$

3.3.2 General Whirl Distribution

The correlation used for the other swirl laws was taken from *Principles of Turbomachinery* (Seppo, 2011), simply changing the n values in the following equations, three different distributions for c_ϑ has been founded:

$$c_\theta = a\mu^n \mp \frac{b}{\mu} \tag{3.17}$$

- *Free Vortex Flow*

This kind of design is obtained using n=-1, at the inlet of the rotor the tangential velocity is:

$$c_{\theta 1,r} = \frac{a}{\mu_1} - \frac{b}{\mu_1} = \frac{a-b}{\mu_1} \quad (3.18)$$

Where a and b are constant and referred to the mean radius:

$$a = U_m(1 - R_m) \quad (3.19)$$

$$b = \frac{1}{2}\psi_m U_m \quad (3.20)$$

It has been said that for this kind of design the axial velocities is constant along the radial direction of the blade so c_m is the same from the hub to the tip.

$$c_{m1} = c_{m1,hub} = c_{m1,tip} \quad (3.21)$$

At the rotor exit c_ϑ is:

$$c_{\theta 2,r} = \frac{a}{\mu_2} + \frac{b}{\mu_2} = \frac{a+b}{\mu_2} \quad (3.22)$$

And c_m

$$c_{m2} = c_{m2,hub} = c_{m2,tip} \quad (3.23)$$

For the outlet of the rotor:

$$c_{\theta 3,r} = \frac{a}{\mu_3} - \frac{b}{\mu_3} = \frac{a-b}{\mu_3} \quad (3.24)$$

$$c_{m3} = c_{m3,hub} = c_{m3,tip} \quad (3.25)$$

The behaviour of the reaction along the radius can be expressed like:

$$R_r = 1 - (1 - R_m)\frac{1}{\mu^2} \tag{3.26}$$

- *Exponential Vortex Flow*

The n values is set equal to zero, this lead to the following distribution for the velocities at the rotor inlet:

$$c_{\theta 1,r} = a - \frac{b}{\mu_1} \tag{3.27}$$

$$c_{m1,r} = c_{m1,m} - \sqrt{2\left[a^2 \log \mu_1 + ab\left(\frac{1}{\mu_1} - 1\right)\right]} \tag{3.28}$$

Now the constant a is

$$a = U_m(R_m - 1) \tag{3.29}$$

Between the rotor and the stator velocities are:

$$c_{\theta 2,r} = a + \frac{b}{\mu_2} \tag{3.30}$$

$$c_{m2,r} = c_{m2,m} - \sqrt{2\left[a^2 \log \mu_2 - ab\left(\frac{1}{\mu_2} - 1\right)\right]} \tag{3.31}$$

Whereas at the outlet of the stage:

$$c_{\theta 3,r} = a - \frac{b}{\mu_3} \tag{3.32}$$

$$c_{m3,r} = c_{m3,m} - \sqrt{2\left[a^2 \log \mu_3 + ab\left(\frac{1}{\mu_3} - 1\right)\right]} \tag{3.33}$$

This time the reaction is:

$$R_r = 1 + (1 - R_m)\left(1 - \frac{2}{\mu}\right) \tag{3.34}$$

- *Constant Reaction Vortex Flow*

This distribution is achieved setting n equals to one, the values of constant a is the same for the free vortex law.
The velocities at the rotor inlet are:

$$c_{\theta 1} = a\mu_1 - \frac{b}{\mu_1} \tag{3.35}$$

$$c_{m1,r} = c_{m1,m} + \sqrt{4ab \log \mu_1 - 2a^2({\mu_1}^2 - 1)} \tag{3.36}$$

Instead for the inlet of the stator:

$$c_{\theta 2} = a\mu_2 + \frac{b}{\mu_2} \tag{3.37}$$

$$c_{m2,r} = c_{m2,m} + \sqrt{-4ab \log \mu_2 - 2a^2({\mu_2}^2 - 1)} \tag{3.38}$$

At the outlet of the stator the same equation for the rotor inlet are used:

$$c_{\theta 3} = a\mu_3 - \frac{b}{\mu_3} \tag{3.39}$$

$$c_{m3,r} = c_{m3,m} + \sqrt{4a \cdot b \log \mu_3 - 2a^2({\mu_3}^2 - 1)} \tag{3.40}$$

For this distribution the trend of reaction is:

$$R_r = 1 - (1 - R_m)(1 - 2\log \mu_3) \tag{3.41}$$

3.4 STAGES AND OUTLET GUIDE VANES PROPERTIES

Once that the axial and absolute tangential are founded all the other characteristic of the flow such the angles and the velocities, and the static, relative and total properties can be found both at the hub and the tip of the blade.

Here only a review of the hub properties has been made, for the tip all the calculation follow the same steps.

3.4.1 Rotor inlet

If the rotor is the first one of the compressor, the axial velocity and α_1 are the same of the inlet specification, in another case, they are the same as the previous stator outlet c_{m3} and α_3, the same is for the total properties.

- Velocities and flow angles

$$U_{1,hub} = \frac{r_{1,hub} \cdot \pi \cdot RPM}{30} \tag{3.42}$$

$$w_{\theta 1,hub} = U_{1,hub} - c_{\theta 1,h} \tag{3.43}$$

$$\beta_{1,hub} = \tan^{-1}\left(\frac{w_{\theta 1,hub}}{c_{m1,hub}}\right) \tag{3.44}$$

$$w_{1,hub} = \frac{c_{m1,hub}}{\cos(\beta_{1,hub})} \tag{3.45}$$

$$c_{1,hub} = \frac{c_{m1,hub}}{\cos(\alpha_{1,hub})} \tag{3.46}$$

- Flow properties

To find the total enthalpy and entropy the *state function* has been used, with the first of this values it is possible to find the static enthalpy, and then all the other static properties:

$$h_{1,hub} = h_{01} - \frac{{c_{1,hub}}^2}{2} \tag{3.47}$$

$$\left.\begin{matrix} h_{1,hub} \\ S_{1,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{1,hub}, T_{1,hub}, Cp_{1,hub}, \rho_{1v}, k_{1,hub}, \nu_{1,hub}, a_{1,hub} \tag{3.48}$$

The speed of sound a_1 is fundamental to find the relative Mach number and the axial Mach number:

$$M_{w1,hub} = \frac{w_{1,hub}}{a_{1,hub}} \tag{3.49}$$

$$M_{cm1,hub} = \frac{c_{m1,hub}}{a_{1,hub}} \tag{3.50}$$

In order to calculate the relative temperature and relative pressure at the inlet of the rotor, is necessary find the total relative enthalpy:

$$h_{01,rel,hub} = h_{1,hub} + {w_{1,hub}}^2 \tag{3.51}$$

$$\left.\begin{matrix} h_{01,rel,hub} \\ S_{1,hub} \end{matrix}\right\} \xrightarrow{state\ properties} p_{01,rel,hub}, T_{01,rel,hub} \tag{3.52}$$

The last step of the rotor inlet is to calculate the rothalpy:

$$I_{1,hub} = h_{1,hub} + \frac{{w_{1,hub}}^2}{2} - \frac{{U_{1,hub}}^2}{2} \tag{3.53}$$

3.4.2 Stator inlet

- Velocities and flow angles

$$U_{2,hub} = \frac{r_{2,hub} \cdot \pi \cdot RPM}{30} \tag{3.54}$$

$$w_{\theta 2,hub} = U_{2,hub} - c_{\theta 2,hub} \tag{3.55}$$

$$c_{2,hub} = \sqrt{{c_{m2,hub}}^2 + c_{\theta 2,hub}^2} \tag{3.56}$$

$$w_{2,hub} = \sqrt{{c_{m2,hub}}^2 + {w_{\theta 2,hub}}^2} \tag{3.57}$$

$$\alpha_{2,hub} = \tan^{-1}\left(\frac{c_{\theta 2,hub}}{c_{m2,hub}}\right) \tag{3.58}$$

$$\beta_{2,hub} = \tan^{-1}\left(\frac{w_{\theta 2,hub}}{c_{m2,hub}}\right) \tag{3.59}$$

- Flow properties

The static enthalpy at the stator inlet can be found from to the rothalpy which is constant across the rotor:

$$I_{2,hub} = I_{1,hub} \tag{3.60}$$

$$h_{2,hub} = I_{2,hub} - \frac{w_{2,hub}^2}{2} + \frac{U_{2,hub}^2}{2} \tag{3.61}$$

To find the static properties at the rotor exit, the exit entropy must be known, it can find from its increase in the rotor, at the beginning with an approximation, then with the correct values thanks to the iteration:

$$S_{2,hub} = S_{1,hub} + \Delta S_{2-1} \tag{3.62}$$

$$\left.\begin{matrix} h_{2,hub} \\ S_{2,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{2,hub}, T_{2,hub}, c_{p2,hub}, \rho_{2,hub}, k_{2,hub}, \upsilon_{2,hub}, a_{2,hub} \tag{3.63}$$

$$M_{c2,hub} = \frac{c_{2,hub}}{a_{2,hub}} \tag{3.64}$$

$$M_{cm,2} = \frac{c_{m2,hub}}{a_{2,hub}} \tag{3.65}$$

The total relative enthalpy, together with the entropy allow to find the relative properties at the stator inlet:

$$h_{02,rel,hub} = h_{2,hub} + \frac{w_{2,hub}^2}{2} \tag{3.66}$$

$$\left.\begin{matrix} h_{02,rel,hub} \\ S_{2,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{02,rel,hub}, T_{02,rel,hub} \tag{3.67}$$

And for the total properties:

$$h_{02,hub} = h_{2,hub} + \frac{c_{2,hub}^2}{2} \tag{3.68}$$

$$\left.\begin{matrix} h_{02,hub} \\ S_{2,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{02,hub}, T_{02,hub} \tag{3.69}$$

Before to continue the calculation for the stator outlet the deHaller number of the rotor has been calculated:

$$dH_{rtr,hub} = \frac{w_{2,hub}}{w_{1,hub}} \tag{3.70}$$

3.4.3 Stator outlet

The last step of the calculations for the stages is the exit of the stator:

- Velocities and flow angles

At the stator outlet does not exists relative components of the velocities:

$$\alpha_{3,hub} = \tan^{-1}\left(\frac{c_{\theta 3,hub}}{c_{m3,hub}}\right) \tag{3.71}$$

$$c_{3,hub} = \frac{c_{m3,hub}}{\cos^{-1}(\alpha_{3,hub})} \tag{3.72}$$

- Flow properties

Across the stator the total enthalpy remain constant, this is fundamental to find the static properties at the outlet:

$$h_{03,hub} = h_{02,hub} \tag{3.73}$$

$$h_{3,hub} = h_{03,hub} - \frac{c_{3,hub}^2}{2} \tag{3.74}$$

$$S_{3,hub} = S_{2,hub} + \Delta S_{3-2} \tag{3.75}$$

$$\left.\begin{matrix} h_{3,hub} \\ S_{3,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{3,hub}, T_{3,hub}, c_{p3,hub}, \rho_{3,hub}, k_{3,hub,} v_{3,hub}, a_{3,hub} \tag{3.76}$$

$$M_{c3,hub} = \frac{c_{3,hub}}{a_{3,hub}} \tag{3.77}$$

$$M_{cm,3} = \frac{c_{m3,hub}}{a_{3,hub}} \tag{3.78}$$

With the total enthalpy is easy to find the total pressure and temperature:

$$\left.\begin{matrix} h_{03,hub} \\ S_{3,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{03,hub}, T_{03,hub} \tag{3.79}$$

As did for the rotor also for the stator the de Haller number has been found:

$$dH_{str,hub} = \frac{c_{3,hub}}{c_{2,hub}} \tag{3.80}$$

3.4.4 Outlet Guide Vanes (OGV)

Once the calculations are finish for all the stages of the compressor, ones for the OGV start. This part of the compressor is another stator placed after the last stage, before the combustion chamber, in order to decrease or eliminate the swirl component of the flow which could interfere with a good combustion.
The steps of calculation are very similar to the stator ones:

- Velocities and flow angles

$$c_{mOGV,hub} = c_{m3,hub} \tag{3.81}$$

$$c_{OGV,hub} = c_{mOGV,hub} \tag{3.82}$$

Since a zero whirl is needed, the axial velocity is equal to the absolute velocity.

- Flow properties

The static properties of the flow in the OGV are:

$$h_{0OGV,hub} = h_{03,hub} \tag{3.83}$$

$$h_{OGV,hub} = h_{0OGV,hub} - \frac{c_{OGV,hub}^2}{2} \tag{3.84}$$

$$S_{OGV,hub} = S_{3,hub} + \Delta S_{OGV} \tag{3.85}$$

$$\left.\begin{matrix} h_{OGV,hub} \\ S_{OGV,hub} \end{matrix}\right\} p_{OGV,hub}, T_{OGV,hub}, c_{pOGV,hub}, \rho_{OGV,hub}, k_{OGV,hub}, \upsilon_{OGV,hub}, a_{OGV,hub} \tag{3.86}$$

$$M_{cOGV,hub} = \frac{c_{OGV,hub}}{a_{OGV,hub}} \tag{3.87}$$

As regards the total properties the total enthalpy of the OGV has been used:

$$\left.\begin{matrix} h_{0OGV,hub} \\ S_{OGV,hub} \end{matrix}\right\} \xrightarrow{state\ function} p_{0OGV,hub}, T_{0OGV,hub} \tag{3.88}$$

And finally, the de Haller number is:

$$dH_{OGV,hub} = \frac{c_{OGV,hub}}{c_{3,hub}} \tag{3.89}$$

3.5 BLADE ANGLES AND DIFFUSION FACTOR

3.5.1 Rotor

In order to find all the blade characteristic at the hub and the tip of the blade, the pitch to chord ratio (*S/c*) and the thickness chord ratio (*t/c*) has to be found:

$$d_{rtr,hub} = 2 \cdot \pi \cdot r_{rtr,hub} \tag{3.90}$$

$$spc_{rtr,hub} = \frac{d_{rtr,hub}}{n_{bl,rtr}} \tag{3.91}$$

$$\left(\frac{S}{c}\right)_{rtr,hub} = \frac{spc_{rtr,hub}}{n_{bl,rtr}} \tag{3.92}$$

$$\left(\frac{t}{c}\right)_{rtr,hub} = \left(\frac{t}{c}\right)_{rtr} \cdot 1{,}5 \tag{3.93}$$

The pitch to chord ratio is found from the diameter of the rotor at the hub, the spacing between the blade and the number of the blades in a row; the thickness is assumed to be 1.5 more than the values at the mid span for the hub and 0.5 for the tip.

The relative inlet and outlet angles are the same of the flow, $\beta_{1,hub}$ and $\beta_{2,hub}$, and the Mach number used is the relative one, with all these parameters set, using the *Blade angles function* all the blade values for the rotor can be found:

$$\left.\begin{matrix} \beta_{1,hub} \\ \beta_{2,hub} \\ \left(\frac{S}{c}\right)_{rtr,hub} \\ \left(\frac{t}{c}\right)_{rtr} \\ M_{w1,hub} \end{matrix}\right\} \xrightarrow{blade\ function} i_{rtr,hub}, \delta_{rtr,hub}, \theta_{rtr,hub}, \gamma_{rtr,hub}, \beta_{b1,hub}, \beta_{b2,hub} \tag{3.94}$$

To find the diffusion factor at the hub and the tip *Deq_star1 function* has been used:

$$\left.\begin{matrix} \beta_{1,hub} \\ \beta_{2,hub} \\ c_{m1,hub} \\ c_{m2,hub} \\ r_{1,hub} \\ r_{2,hub} \\ \left(\frac{S}{c}\right)_{rtr,hub} \\ \left(\frac{t}{c}\right)_{rtr,hub} \\ AVDR_{rtr} \\ M_{cm1,hub} \end{matrix}\right\} \xrightarrow{Deq\_star1} \left(D_{eq,rtr,hub}\right), \left(D^*_{eq,rtr,hub}\right)_{Lieblein}, \left(D^*_{eq,rtr,hub}\right)_{KochSmith} \tag{3.95}$$

3.5.2 Stator blade angles

The thickness of the stator is assumed to be constant in the radial direction of the blade, and this time the relative inlet and outlet angles are $\alpha_{2,hub}$ and $\alpha_{3,hub}$.

$$d_{rs,hub} = 2 \cdot \pi \cdot r_{str,hub} \tag{3.96}$$

$$spc_{rs,hub} = \frac{d_{str,hub}}{n_{bl,str}} \tag{3.97}$$

$$\left(\frac{S}{c}\right)_{str,hub} = \frac{spc_{str,hub}}{n_{bl,str}} \tag{3.98}$$

$$\left.\begin{matrix} \alpha_{2,hub} \\ \alpha_{3,hub} \\ \left(\frac{S}{c}\right)_{str,hub} \\ \left(\frac{t}{c}\right)_{str} \\ M_{c2,hub} \end{matrix}\right\} \xrightarrow{blade\ function} i_{str,hub}, \delta_{str,hub}, \theta_{str,hub}, \gamma_{str,hub}, \alpha_{b2,hub}, \alpha_{b3,hub} \tag{3.99}$$

The diffusion factors are founded from:

$$\left.\begin{matrix} \alpha_{2,hub} \\ \alpha_{3,hub} \\ c_{m2,hub} \\ c_{m3,hub} \\ r_{2,hub} \\ r_{3,hub} \\ \left(\frac{S}{c}\right)_{str,hub} \\ \left(\frac{t}{c}\right)_{str} \\ AVDR_{str} \\ M_{cm2,hub} \end{matrix}\right\} \xrightarrow{Deq\_star1} \left(D_{eq,rtr,hub}\right), \left(D^{*}_{eq,rtr,hub}\right)_{Lieblein}, \left(D^{*}_{eq,rtr,hub}\right)_{KochSmith} \tag{3.100}$$

The same procedure is applied at the OGV with $\alpha_{3,hub}$ as relative inlet angle and zero as relative outlet angle.

3.6 BLADE SHAPE

In the past, blade designs are standardized, divided in two big families of airfoils, one used in America practice, defined by the National Advisory Committee for Aeronautics (NACA); the other, used in british practice, referred to a circular-arc or parabolic-arc camberlines (C-series family).

Recently, with the grow of specific application, and the need of more efficiency profiles, inverse design method is used; thus the blade is modelled in order to satisfy the required loading and flow behaviour; however this airfoil designs are always proprietary.

The blade profile adopted in this work is the double circular arc, used for compressor operating at subsonic inlet Mach numbers more than 0.5 (high subsonic), and trans-sonic one; all the mathematic formulation are taken from Aungier.

The camberline of the blade is a circular arc defined by the camber angle, ϑ, and the chord length c, from them is possible to find the radius of curvature:

$$R_c = \frac{c}{2}\frac{1}{\sin(\theta/2)} \tag{3.101}$$

The origin of this radius is located in $(0,y_c)$:

$$y_c = -R_c \cos\left(\frac{\theta}{2}\right) \tag{3.102}$$

Thus it is possible to have the trend of the curve:

$$y = y_c + \sqrt{R_c^2 - x^2} \tag{3.103}$$

where x goes from –c/2 to c/2.

The leading and trailing edge of this airfoil family are made up of two nose of radius r_0 which connect the suction and the pressure side.
The radius of the upper surface is:

$$R_u = \frac{d^2 - r_0^2 + [c/2 - r_0 \cos(\theta/2)]^2}{2(d - r_0)} \tag{3.104}$$

Where d is:

$$d = y(0) + \frac{t_b}{2} - r_0 \sin\left(\frac{\theta}{2}\right) \tag{3.105}$$

y(0) is the camberline coordinate at mid chord:

$$y(0) = \frac{c}{2} \tan\left(\frac{\theta}{4}\right) \tag{3.106}$$

and t_b is the maximum thickness of the blade.
The distance from the centre of the nose and the mid-chord is:

$$\Delta x_u = \frac{c}{2} - r_0 \cos\left(\frac{\theta}{2}\right) \tag{3.107}$$

The origin of the suction side is:

$$y_{u,0} = y(0) + \frac{t_b}{2} - R_u \tag{3.108}$$

The upper surface is obtained from:

$$y_u = y_{u,0} + \sqrt{R_u^2 - x_u^2} \tag{3.109}$$

x_u is included from $-\Delta x_u$ and Δx_u.
The pressure surface can be obtained in the same way using negative values for t_b and r_0.

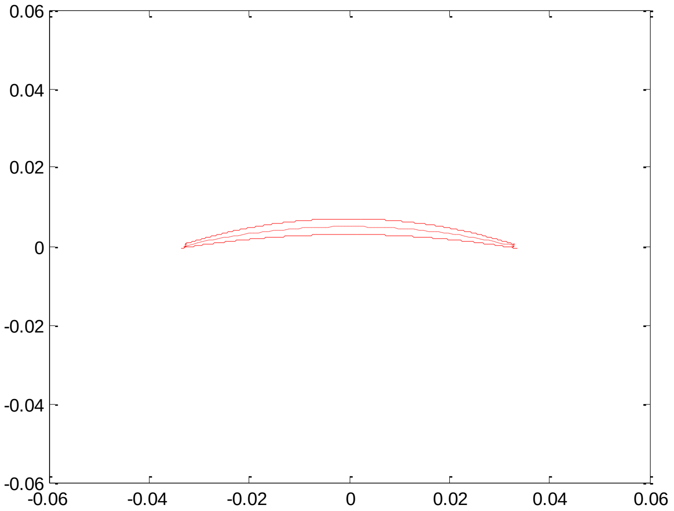


Figure 3-4 Matlab plot of a double circular arc profile

To get the staggered blade geometry a rotation of coordinates to the stagger angle, γ, has been made:

$$x_{staggered} = x\cos(\gamma) - y\sin(\gamma) \qquad (3.110)$$

$$y_{staggered} = x\sin(\gamma) + y\tan(\gamma) \qquad (3.111)$$

CHAPTER 4 APPLICATION

A simulation for an axial compressor has been made to show how the code work and the results that it produce.

The next table showed the characteristic chosen for the compressor:

Number of stages	16
Mass flow	122 [kg/s]
Pressure ratio	20
Rotational speed	6600 [rpm]
Reaction	0.55

Table 1 Main characteristic of the compressor

The *constant exit hub to tip ratio* has been selected for the compressor type field, thus the AVR along the compressor does not need to be set anymore; the chosen swirl law is the *forced vortex* one.

For the inlet specification the values are:

α	15
Φ	0.65
H/T	0.52

Table 2 Inlet specification

The other specifications along the compressor are:

	First stage	**Last stage**
ε/c		
Rotor	0.02	0.02
Stator	0	0

H/c		
Rotor	2.5	1
Stator	3.5	1

	First stage	**Last stage**
T/c		
Rotor	0.06	0.06
Stator	0.06	0.06
DF		
Rotor	0.45	0.45
Stator	0.45	0.45
BLK	0.98	0.88

The outlet velocity at the OGV is set at 130 and the distribution of the loading, Φ, start from1 and decrease until 0.8 at the end of the compressor.

Once that all these parameters are fixed, the code can be run; when all the iteration are conclude, the compressor flow path and the velocity diagrams for each stage appears (Figure 4-1).

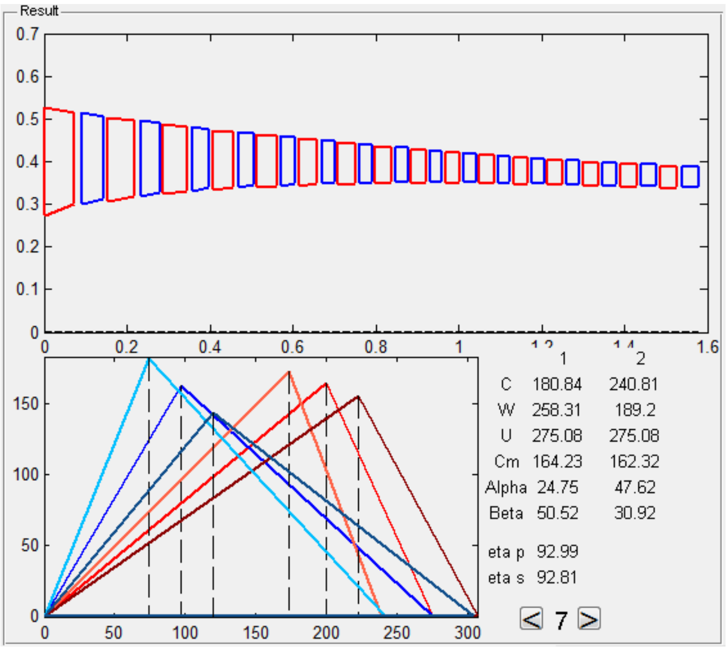


Figure 4-1 Flow path and velocity diagrams from the hub to the tip

The red coloured line are used for the rotor and the blue one for the stator, the paler colour specify the velocity diagram for the hub of the blade, and the darker colour the velocity diagram for the tip.

The behaviour of the velocity is what we expect, indeed the forced vortex swirl law involve the increase of tangential velocity from the hub to the tip to balance the coincident increase of pressure.

The main characteristics of the compressor can be found in the *Result file* printed in Windows block notes format, in order to be clear and simple to read.

Polytropic efficiency	92.69 %
Isentropic efficiency	90.91 %
Temperature rise	422.5 [K]
Inlet Mach @ tip	1.08
Specific massflow	231.4 [kg/(s m^2)]
Compressor power	53.31 [MW]

Table 3 Compressor performance

LUAX-C also plot the shape of the blade for each stage, both for the rotor and the stator, thus it is possible to check how their physics characteristic and dimension changes along the compressor.

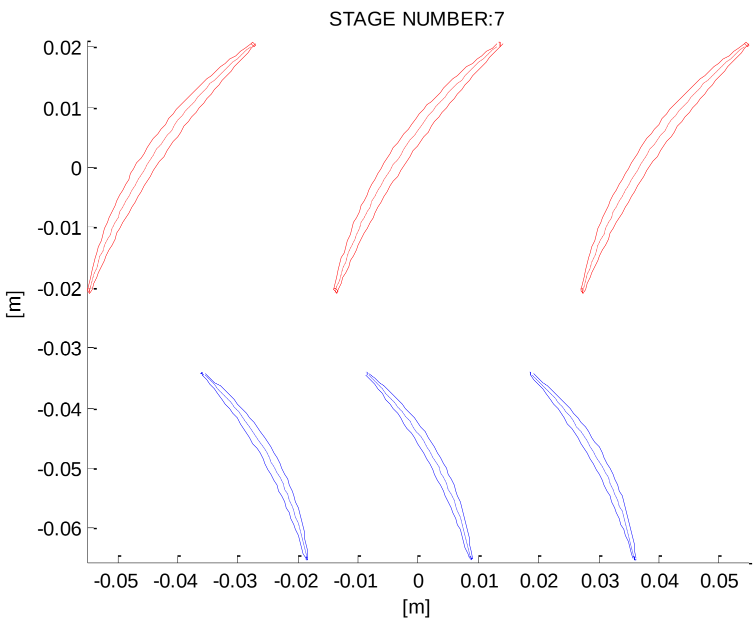
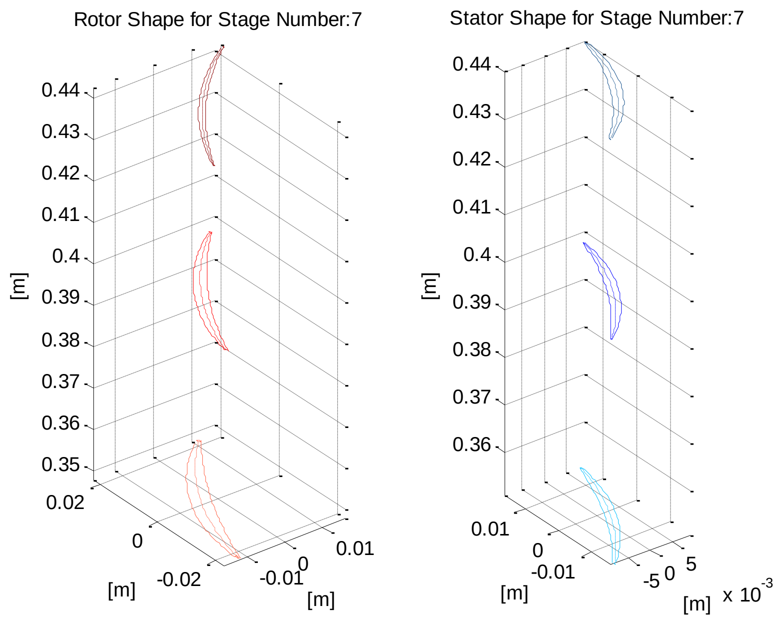


Figure 4-2 mid span blade shape

Another plot permitted by this new version of LUAX-C is the behaviour of the blade along its span both for the rotor and the stator.

Rotating the view allow to have a better idea of the influence of the chosen swirl vortex on the blade shape.



All the results have been confronted with literature, the behaviour of the velocity from the hub to the tip for each swirl law, match with the existing dates (Aungier, 2003) at same initial parameters.

CHAPTER 5 USER'S GUIDE

In order to permit the choice of the swirl law and the new compressor type needed for the design of the compressor, and the plot of the blade shape, the pre-existing GUI, Graphic User Interface, has been modified.

When *constant exit hut tip ratio* is select, C_OGV window appears, and the Axial Velocity Ratio one disappear because now is useless.

Furthermore choosing the *General Whirl Distribution*, the window for the pick of the *n* values come into view, consent to select the desire swirl law (Figure 5-1).

Another extension make is the chance to do another bleed, improving the control on stall.

To start the calculation, after that all the parameters has been chosen, clicking on *Create Data File* the input file will be created in a text file form where is also possible to change all the dates.

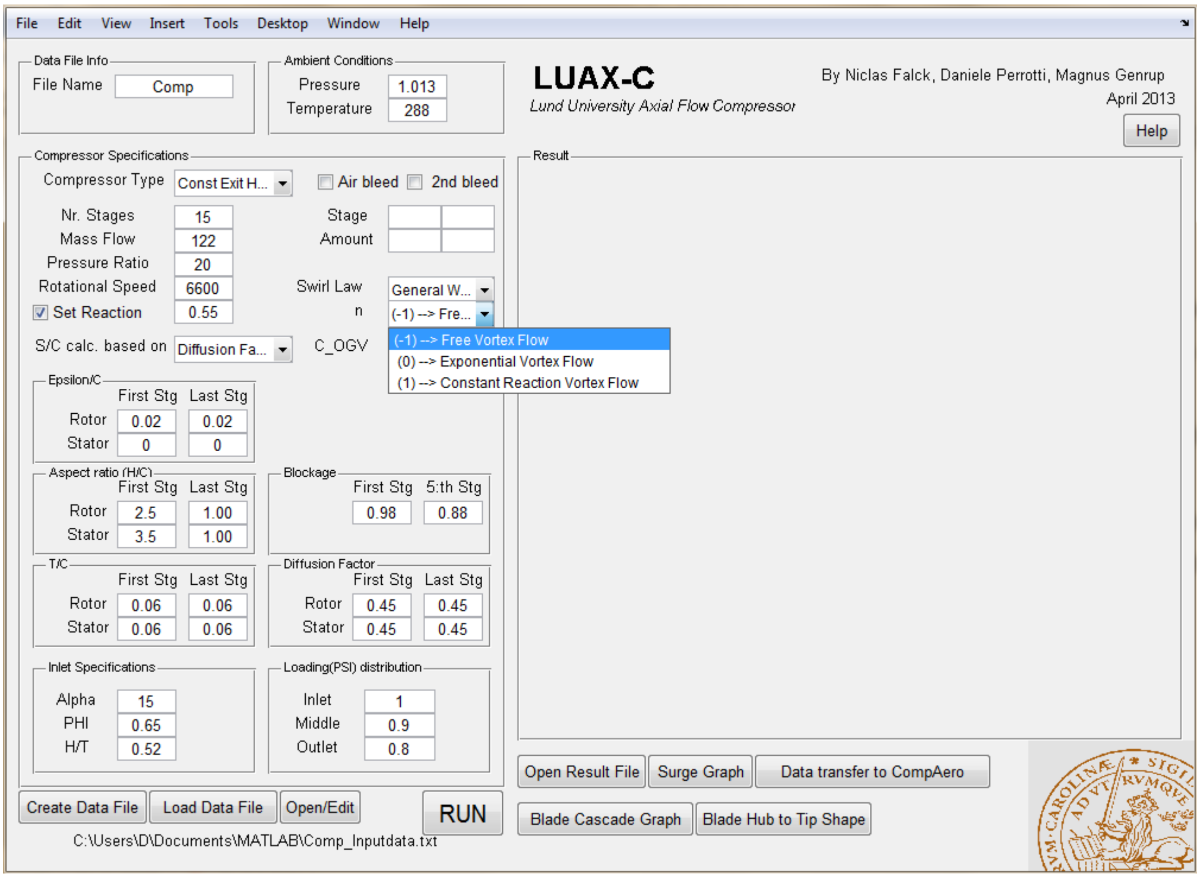


Figure 5-1 LUAX-C Main Window

Now is possible to start the calculation, selecting the *RUN* button, once all the loop are terminated, both the shape of the flow path and the velocity diagrams appears; the duration of this process can take some minutes, it depends from the performance of the calculator.

The *Open Result File* button open a Windows note file that contains all the result, from the first stage to the OGV.

Two new buttons have been added, *Blade Path Graph*, which plot the rotor and the stator airfoil at the mid-span, together for each stages, and *Blade Hub to Tip Shape*, which plot the blade shape in the three positions.

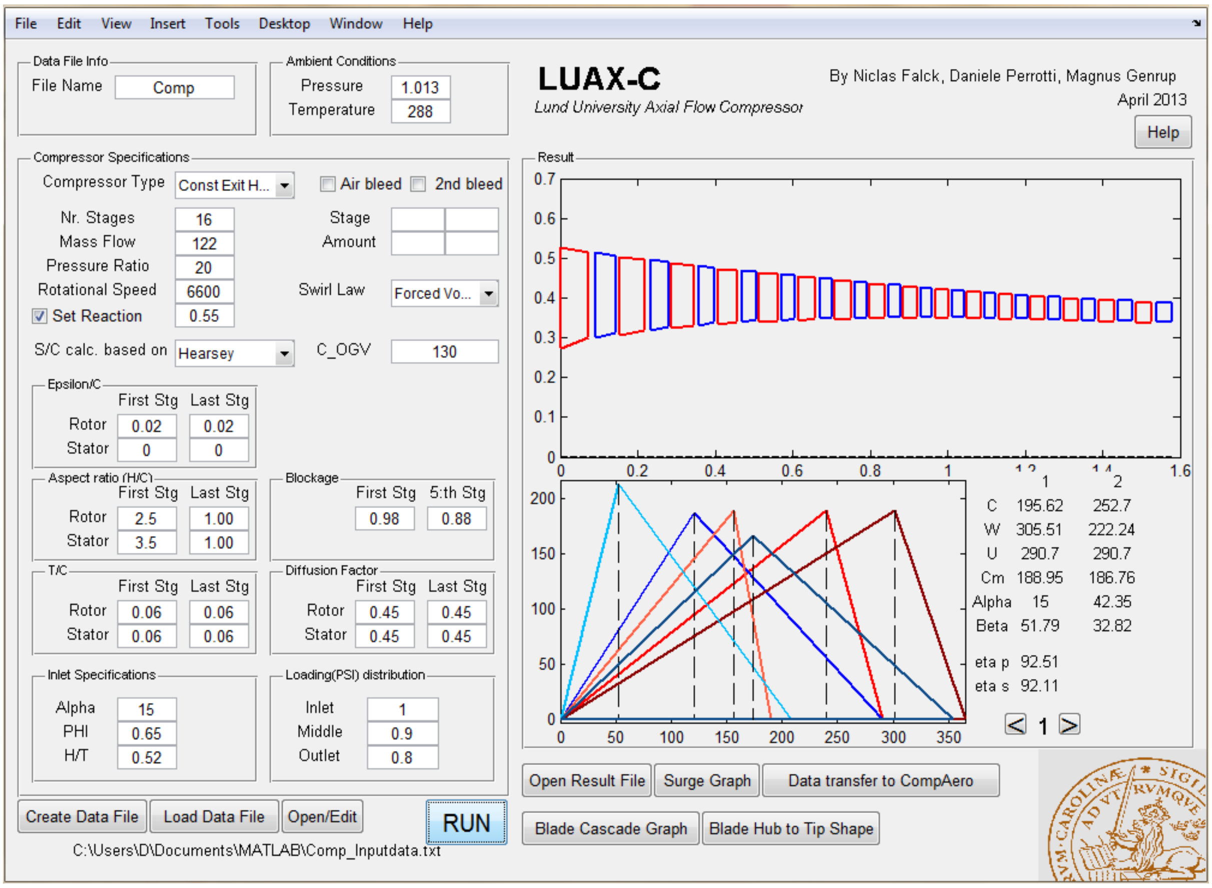


Figure 5-2 Complete run window

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APPENDIX

A, Table of figures

B, Matlab code

B1, Forced vortex law

```
%######################################################################
%##                                                                  ##
%##                        Forced Vortex law                         ##
%##                                                                  ##
%##                       Daniele Perrotti 2013                      ##
%##                                                                  ##
%##            Lund University/Dept of Energy Sciences               ##
%##                                                                  ##
%######################################################################




globalvariables %call for the global variables
global i flow j

%########### Forced Vortex for compressor stages ##########



%###########################################################
%############### Station 1 Forced Vortex law ##############
%###########################################################

%C1_FV_hub

C_theta1_FV_hub(i)=Cm1(i)*((r_hub_1(i)/r_rms_1(i))*tand(Alpha1(i)));
%C_theta1 at the hub
Cm1_FV_hub(i)=(1+2*((tand(Alpha1(i))^2*(1-
(r_hub_1(i)/r_rms_1(i))^2))))^0.5*Cm1(i);
U1_FV_hub(i)=r_hub_1(i)*pi*RPM/30;

W_theta1_FV_hub(i) = U1_FV_hub(i)-C_theta1_FV_hub(i);
Beta1_FV_hub(i) = atand(W_theta1_FV_hub(i)/Cm1_FV_hub(i));

W1_FV_hub(i) = Cm1_FV_hub(i)/cosd(Beta1_FV_hub(i));

%C1_FV_tip

C_theta1_FV_tip(i)=Cm1(i)*(r_tip_1(i)/r_rms_1(i))*tand(Alpha1(i));
%C_theta1 at the tip
Cm1_FV_tip(i)=(1+2*((tand(Alpha1(i))^2*(1-
(r_tip_1(i)/r_rms_1(i))^2))))^0.5*Cm1(i); %Cm1 at the tip
U1_FV_tip(i)=r_tip_1(i)*pi*RPM/30;

W_theta1_FV_tip(i) = U1_FV_tip(i)-C_theta1_FV_tip(i);
Beta1_FV_tip(i) = atand(W_theta1_FV_tip(i)/Cm1_FV_tip(i));

W1_FV_tip(i) = Cm1_FV_tip(i)/cosd(Beta1_FV_tip(i));
```

```
%################## Station 1 Forced Vortex Rotor inlet #################

%#### HUB

if i==1

    Cm1_FV_hub(i) = Cm_in;
    Alpha1_FV_hub(i) = Alpha_in;
else


    Alpha1_FV_hub(i) = Alpha3_FV_hub(i-1);
end

C1_FV_hub(i) = Cm1_FV_hub(i)/cosd(Alpha1_FV_hub(i));

%#### TIP

if i==1

    Cm1_FV_tip(i) = Cm_in;
    Alpha1_FV_tip(i) = Alpha_in;
else

    Alpha1_FV_tip(i) = Alpha3_FV_tip(i-1);
end

C1_FV_tip(i) = Cm1_FV_tip(i)/cosd(Alpha1_FV_tip(i));

%################ Station 1 Forced Vortex total properties ##############

%#### HUB
if i==1 % The first stage
    P01_FV_hub(i) = P0_in;
    T01_FV_hub(i) = T0_in;
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV,
y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('PT',P01_FV_hub(i),T01_FV_hub(i),0,1);
    H01_FV_hub(i) = H;
%     S01(i) = S;
%     S1(i) = S;
else
    P01_FV_hub(i) = P03_FV_hub(i-1);
    T01_FV_hub(i) = T03_FV_hub(i-1);
    H01_FV_hub(i) = H03_FV_hub(i-1);
%     S01(i) = S3(i-1);
%     S1(i) = S3(i-1);
end

%#### TIP
if i==1 % The first stage
    P01_FV_tip(i) = P0_in;
    T01_FV_tip(i) = T0_in;
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV,
y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('PT',P01_FV_tip(i),T01_FV_tip(i),0,1);
    H01_FV_tip(i) = H;
%     S01(i) = S01;
%     S1(i) = S1;
```

```
else
    P01_FV_tip(i) = P03_FV_tip(i-1);
    T01_FV_tip(i) = T03_FV_tip(i-1);
    H01_FV_tip(i) = H03_FV_tip(i-1);
%      S01(i) = S3(i-1);
%      S1(i) = S3(i-1);
end
%################# Station 1 FV static properties ############

%######## at the Hub

H1_FV_hub(i) = H01(i)-(C1_FV_hub(i)^2)/2; % Static enthalpy at rotor inlet
FV

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H1_FV_hub(i),S1(i),0,1);
P1_FV_hub(i) = P;
T1_FV_hub(i) = T;
Cp1_FV_hub(i) = Cp;
rho1_FV_hub(i) = rho;
Visc1_FV_hub(i) = Visc;
kappa1_FV_hub(i) = kappa;
a1_FV_hub(i) = a;

MW1_FV_hub(i) = W1_FV_hub(i)/a1_FV_hub(i); % Station 1 relative  Mach
FV_hub

MCm1_FV_hub(i) = Cm1_FV_hub(i)/a1_FV_hub(i); % Relative inlet meridional
Mach FV_hub

%####### at the Tip

H1_FV_tip(i) = H01(i)-(C1_FV_tip(i)^2)/2; % Static enthalpy at rotor inlet
FV

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H1_FV_tip(i),S1(i),0,1);
P1_FV_tip(i) = P;
T1_FV_tip(i) = T;
Cp1_FV_tip(i) = Cp;
rho1_FV_tip(i) = rho;
Visc1_FV_tip(i) = Visc;
kappa1_FV_tip(i) = kappa;
a1_FV_tip(i) = a;

MW1_FV_tip(i) = W1_FV_tip(i)/a1_FV_tip(i); % Station 1 relative  Mach
FV_tip

MCm1_FV_tip(i) = Cm1_FV_tip(i)/a1_FV_tip(i); % Relative inlet meridional
Mach FV_tip

%############# Station 1 FV relative properties ##############

%######## at the Hub

H01_rel_FV_hub(i) = H1_FV_hub(i)+ (W1_FV_hub(i)^2)/2; % Relative total
enthalpy
```

```
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H01_rel_FV_hub(i),S1(i),0,1);
P01_rel_FV_hub(i) = P;
T01_rel_FV_hub(i) = T;

I1_FV_hub(i) = H1_FV_hub(i)+(W1_FV_hub(i)^2)/2-(U1_FV_hub(i)^2)/2; %
Station 1 rothalpy at the hub

%####### at the Tip

H01_rel_FV_tip(i) = H1_FV_tip(i)+ (W1_FV_tip(i)^2)/2; % Relative total
enthalpy at the tip
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H01_rel_FV_tip(i),S1(i),0,1);
P01_rel_FV_tip(i) = P;
T01_rel_FV_tip(i) = T;

I1_FV_tip(i) = H1_FV_tip(i)+(W1_FV_tip(i)^2)/2-(U1_FV_tip(i)^2)/2; %
Station 1 rothalpy at the tip


%###################################################
%############### Station 2 Forced Vortex law ######
%###################################################

% C2_FV_hub

C_theta2_FV_hub(i)=Cm2(i)*(tand(Alpha1(i))*(r_hub_2(i)/r_rms_2(i))+(PSI(j,i
)/(Cm2(i)/U2(i))));
Cm2_FV_hub(i)=Cm2(i)*((1+2*((tand(Alpha1(i))^2)*(1-
(r_hub_2(i)/r_rms_2(i))^2))-
4*(tand(Alpha1(i))*(PSI(j,i)/(Cm2(i)/U2(i)))*log(r_hub_2(i)/r_rms_2(i)))))^
0.5;


U2_FV_hub(i)=r_hub_2(i)*pi*RPM/30;

W_theta2_FV_hub(i) = U2_FV_hub(i)-C_theta2_FV_hub(i);
C2_FV_hub(i) = (Cm2_FV_hub(i)^2+C_theta2_FV_hub(i)^2)^0.5;
W2_FV_hub(i) = (Cm2_FV_hub(i)^2+W_theta2_FV_hub(i)^2)^0.5;
Alpha2_FV_hub(i) = atand(C_theta2_FV_hub(i)/Cm2_FV_hub(i));
Beta2_FV_hub(i) = atand(W_theta2_FV_hub(i)/Cm2_FV_hub(i));


% C2_FV_tip

C_theta2_FV_tip(i)=Cm2(i)*(tand(Alpha1(i))*(r_tip_2(i)/r_rms_2(i))+(PSI(j,i
)/(Cm2(i)/U2(i))));
Cm2_FV_tip(i)=Cm2(i)*((1+2*((tand(Alpha1(i))^2)*(1-
(r_tip_2(i)/r_rms_2(i))^2))-
4*(tand(Alpha1(i))*(PSI(j,i)/(Cm2(i)/U2(i)))*log(r_tip_2(i)/r_rms_2(i)))))^
0.5;

U2_FV_tip(i)=r_tip_2(i)*pi*RPM/30;

W_theta2_FV_tip(i) = U2_FV_tip(i)-C_theta2_FV_tip(i);
```

```
C2_FV_tip(i) = (Cm2_FV_tip(i)^2+C_theta2_FV_tip(i)^2)^0.5;
W2_FV_tip(i) = (Cm2_FV_tip(i)^2+W_theta2_FV_tip(i)^2)^0.5;
Alpha2_FV_tip(i) = atand(C_theta2_FV_tip(i)/Cm2_FV_tip(i));
Beta2_FV_tip(i) = atand(W_theta2_FV_tip(i)/Cm2_FV_tip(i));


%########### Station 2 FV  static properties ###########

%##### at the hub

S2(i) = S1(i)+dS21(i);

I2_FV_hub(i) = I1_FV_hub(i); %I.e. constant rothalpy through a rotor

H2_FV_hub(i) = I2_FV_hub(i)-(W2_FV_hub(i)^2)/2+(U2_FV_hub(i)^2)/2;

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] = state('HS',
H2_FV_hub(i),S2(i),0,1);
P2_FV_hub(i) = P;
T2_FV_hub(i) = T;
Cp2_FV_hub(i) = Cp;
rho2_FV_hub(i) = rho;
Visc2_FV_hub(i) = Visc;
kappa2_FV_hub(i) = kappa;
a2_FV_hub(i) = a;

MC2_FV_hub(i) = C2_FV_hub(i)/a2_FV_hub(i); % Absolute inlet Mach FV_hub#

MCm2_FV_hub(i) = Cm2_FV_hub(i)/a2_FV_hub(i); % Relative inlet meridional
Mach FV_hub#

%#### at the tip
S2(i) = S1(i)+dS21(i);

I2_FV_tip(i) = I1_FV_tip(i); %I.e. constant rothalpy through a rotor

H2_FV_tip(i) = I2_FV_tip(i)-(W2_FV_tip(i)^2)/2+(U2_FV_tip(i)^2)/2;

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] = state('HS',H2_FV_tip(i),S2(i),0,1);
P2_FV_tip(i) = P;
T2_FV_tip(i) = T;
Cp2_FV_tip(i) = Cp;
rho2_FV_tip(i) = rho;
Visc2_FV_tip(i) = Visc;
kappa2_FV_tip(i) = kappa;
a2_FV_tip(i) = a;

MC2_FV_tip(i) = C2_FV_tip(i)/a2_FV_tip(i); % Absolute inlet Mach FV_tip

MCm2_FV_tip(i) = Cm2_FV_tip(i)/a2_FV_tip(i); % Relative inlet meridional
Mach FV_tip



%############# Station 2 FV relative properties #############
```

```
%##### at the hub

H02_rel_FV_hub(i) = H2_FV_hub(i)+ (W2_FV_hub(i)^2)/2; % Relative total
enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H02_rel_FV_hub(i),S2(i),0,1);
P02_rel_FV_hub(i) = P;
T02_rel_FV_hub(i) = T;


%##### at the tip

H02_rel_FV_tip(i) = H2_FV_tip(i)+ (W2_FV_tip(i)^2)/2; % Relative total
enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H02_rel_FV_tip(i),S2(i),0,1);
P02_rel_FV_tip(i) = P;
T02_rel_FV_tip(i) = T;



%########### Station 2 FV total properties ###########

%##### at the hub

H02_FV_hub(i) = H2_FV_hub(i)+(C2_FV_hub(i)^2)/2; % Exit total enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] =
state('HS',H02_FV_hub(i),S2(i),0,1);
P02_FV_hub(i) = P;
T02_FV_hub(i) = T;

%##### at the tip

H02_FV_tip(i) = H2_FV_tip(i)+(C2_FV_tip(i)^2)/2; % Exit total enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] =
state('HS',H02_FV_tip(i),S2(i),0,1);
P02_FV_tip(i) = P;
T02_FV_tip(i) = T;

%######## deHaller number Forced Vortex law rtr

%##### at the hub
dH_rtr_FV_hub(i)=W2_FV_hub(i)/W1_FV_hub(i);

%#### at the tip
dH_rtr_FV_tip(i)=W2_FV_tip(i)/W1_FV_tip(i);

%###################################################
%############Station 3 Forced Vortex law###########
%###################################################

% C3_FV_hub
C_theta3_FV_hub(i)=Cm3(i)*(r_hub_3(i)/r_rms_3(i))*tand(Alpha1(i));
%C_theta3 at the hub
```

```
Cm3_FV_hub(i)=Cm3(i)*sqrt(1+2*tand(Alpha1(i))^2*(1-
(r_hub_3(i)/r_rms_3(i))^2)); %Cm3 at the hub
Alpha3_FV_hub(i) = atand(C_theta3_FV_hub(i)/Cm3_FV_hub(i));
C3_FV_hub(i) = Cm3_FV_hub(i)/cosd(Alpha3_FV_hub(i));


% C3_FV_tip
C_theta3_FV_tip(i)=Cm3(i)*(r_tip_3(i)/r_rms_3(i))*tand(Alpha1(i));%C_theta3
at the tip
Cm3_FV_tip(i)=Cm3(i)*sqrt(1+2*tand(Alpha1(i))^2*(1-
(r_tip_3(i)/r_rms_3(i))^2)); %Cm3 at the tip
Alpha3_FV_tip(i) = atand(C_theta3_FV_tip(i)/Cm3_FV_tip(i));
C3_FV_tip(i) = Cm3_FV_tip(i)/cosd(Alpha3_FV_tip(i));


%########### Station 3 FV static properties ##########

%#### HUB

H03_FV_hub(i) = H02_FV_hub(i); % Constant total enthalpy through the stator
H3_FV_hub(i) = H03_FV_hub(i)-(C3_FV_hub(i)^2)/2;
S3(i) = S2(i)+dS32(i);
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H3_FV_hub(i),S3(i),0,1);
P3_FV_hub(i) = P;
T3_FV_hub(i) = T;
Cp3_FV_hub(i) = Cp;
rho3_FV_hub(i) = rho;
Visc3_FV_hub(i) = Visc;
kappa3_FV_hub(i) = kappa;
a3_FV_hub(i) = a;

MC3_FV_hub(i) = C3_FV_hub(i)/a3_FV_hub(i);% Absolute inlet Mach FV_hub #

MCm3_FV_hub(i) = Cm3_FV_hub(i)/a3_FV_hub(i);% Relative inlet meridional
Mach FV_hub #

%#### TIP

H03_FV_tip(i) = H02_FV_tip(i); % Constant total enthalpy through the stator
H3_FV_tip(i) = H03_FV_tip(i)-(C3_FV_tip(i)^2)/2;
S3(i) = S2(i)+dS32(i);
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H3_FV_tip(i),S3(i),0,1);
P3_FV_tip(i) = P;
T3_FV_tip(i) = T;
Cp3_FV_tip(i) = Cp;
rho3_FV_tip(i) = rho;
Visc3_FV_tip(i) = Visc;
kappa3_FV_tip(i) = kappa;
a3_FV_tip(i) = a;

MC3_FV_tip(i) = C3_FV_hub(i)/a3_FV_hub(i);% Absolute inlet Mach FV_hub #

MCm3_FV_tip(i) = Cm3_FV_hub(i)/a3_FV_hub(i);% Relative inlet meridional
Mach FV_hub #

%############ Station 3 FV total properties ##########
```

```
%#### HUB
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H03_FV_hub(i),S3(i),0,1);
P03_FV_hub(i) = P;
T03_FV_hub(i) = T;

%#### TIP

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',H03_FV_tip(i),S3(i),0,1);
P03_FV_tip(i) = P;
T03_FV_tip(i) = T;

%######## deHaller number Forced Vortex law str
%#### at the hub
dH_str_FV_hub(i) = C3_FV_hub(i)/C2_FV_hub(i);

%####at the tip
dH_str_FV_tip(i) = C3_FV_tip(i)/C2_FV_tip(i);
```

B2, General Whirl Distribution

```
%##########################################################################
%##                                                                      ##
%##                    General Whirl Distribution                        ##
%##                      Daniele Perrotti 2013                           ##
%##                Lund University/Dept of Energy Sciences               ##
%##########################################################################

globalvariables %call for the global variables
global i flow j k REACT

%######################################################################
%############### Station 1 General Whirl Distribution ###############
%######################################################################

% values of the costants

 if n =='FVF'
     n=-1;
 elseif n =='EVF'
     n=0;
  elseif n=='CRF'
     n=1;
 end



 if  n==0;

  aa(i)=abs(U1(i)*(REACT(i)-1));
 elseif n==-1;
      aa(i)=U1(i)*(1-REACT(i));
   elseif n==1
      aa(i)=U1(i)*(1-REACT(i));
```

```
 end

bb(i)=1/2*(PSI(j,i)*U1(i));

%#### C_theta1 FREE VORTEX LAW
C_theta1_FREEV_hub(i)=aa(i)*(r_hub_1(i)/r_rms_1(i))^(n)-
bb(i)/(r_hub_1(i)/r_rms_1(i));
C_theta1_FREEV_tip(i)=aa(i)*(r_tip_1(i)/r_rms_1(i))^(n)-
bb(i)/(r_tip_1(i)/r_rms_1(i));

%#### Cm1 FREE VORTEX LAW

if n==-1
    %  Cm1_FREEV_hub
   Cm1_FREEV_hub(i)=Cm1(i);
   Cm1_FREEV_tip(i)=Cm1(i);
 elseif n==0

%      Cm1_FREEV_hub
     Cm1_FREEV_hub(i)=sqrt(Cm1(i)^2-
(2*(aa(i)^2*log(r_hub_1(i)/r_rms_1(i))+aa(i)*bb(i)*(1/(r_hub_1(i)/r_rms_1(i
))-1))));
%      Cm1_FREEV_tip
     Cm1_FREEV_tip(i)=sqrt(Cm1(i)^2-
(2*(aa(i)^2*log(r_tip_1(i)/r_rms_1(i))+aa(i)*bb(i)*(1/(r_tip_1(i)/r_rms_1(i
))-1))));
elseif n==1

%     Cm1_FREEV_hub

Cm1_FREEV_hub(i)=sqrt(Cm1(i)^2+(4*aa(i)*bb(i)*log(r_hub_1(i)/r_rms_1(i))-
2*aa(i)^2*((r_hub_1(i)/r_rms_1(i))^2-1)));
%     Cm1_FREEV_tip

Cm1_FREEV_tip(i)=sqrt(Cm1(i)^2+(4*aa(i)*bb(i)*log(r_tip_1(i)/r_rms_1(i))-
2*aa(i)^2*((r_tip_1(i)/r_rms_1(i))^2-1)));

end


 %W1_FREEV_hub
 U1_FREEV_hub(i)=r_hub_1(i)*pi*RPM/30;

 W_theta1_FREEV_hub(i) = U1_FREEV_hub(i)-C_theta1_FREEV_hub(i);
 Beta1_FREEV_hub(i) = atand(W_theta1_FREEV_hub(i)/Cm1_FREEV_hub(i));
 W1_FREEV_hub(i) = Cm1_FREEV_hub(i)/cosd(Beta1_FREEV_hub(i));


 %W1_FREEV_tip
 U1_FREEV_tip(i)=r_tip_1(i)*pi*RPM/30;

 W_theta1_FREEV_tip(i) = U1_FREEV_tip(i)-C_theta1_FREEV_tip(i);
 Beta1_FREEV_tip(i) = atand(W_theta1_FREEV_tip(i)/Cm1_FREEV_tip(i));
 W1_FREEV_tip(i) = Cm1_FREEV_tip(i)/cosd(Beta1_FREEV_tip(i));


%  ################# Station 1 General Whirl Distribution Rotor inlet ####
```

```
%#### HUB

if i==1
    Cm1_FREEV_hub(i) = Cm_in;
    Alpha1_FREEV_hub(i) = Alpha_in;

    else
     Alpha1_FREEV_hub(i) = Alpha3_FREEV_hub(i-1);

end

C1_FREEV_hub(i) = Cm1_FREEV_hub(i)/cosd(Alpha1_FREEV_hub(i));

%#### TIP

if i==1

    Cm1_FREEV_tip(i) = Cm_in;
    Alpha1_FREEV_tip(i) = Alpha_in;
     else

     Alpha1_FREEV_tip(i) = Alpha3_FREEV_tip(i-1);
end

C1_FREEV_tip(i) = Cm1_FREEV_tip(i)/cosd(Alpha1_FREEV_tip(i));


%################ Station 1 General Whirl Distribution total properties
##############

%#### HUB
if i==1 % The first stage
    P01_FREEV_hub(i) = P0_in;
    T01_FREEV_hub(i) = T0_in;
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV,
y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('PT',P01_FREEV_hub(i),T01_FREEV_hub(i),0,1);
    H01_FREEV_hub(i) = H;
%      S01(i) = S;
%      S1(i) = S;
else
    P01_FREEV_hub(i) = P03_FREEV_hub(i-1);
    T01_FREEV_hub(i) = T03_FREEV_hub(i-1);
    H01_FREEV_hub(i) = H03_FREEV_hub(i-1);
%      S01(i) = S3(i-1);
%      S1(i) = S3(i-1);
end

 %#### TIP
 if i==1 % The first stage
     P01_FREEV_tip(i) = P0_in;
     T01_FREEV_tip(i) = T0_in;
     [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV,
y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('PT',P01_FREEV_tip(i),T01_FREEV_tip(i),0,1);
     H01_FREEV_tip(i) = H;
%       S01(i) = S;
%       S1(i) = S;
 else
```

```
      P01_FREEV_tip(i) = P03_FREEV_tip(i-1);
      T01_FREEV_tip(i) = T03_FREEV_tip(i-1);
      H01_FREEV_tip(i) = H03_FREEV_tip(i-1);
%       S01(i) = S3(i-1);
%       S1(i) = S3(i-1);
  end

 %################## Station 1 General Whirl Distribution static properties
############

 %######### at the Hub

 H1_FREEV_hub(i) = H01(i)-(C1_FREEV_hub(i)^2)/2; % Static enthalpy at rotor
inlet FREEV

 [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H1_FREEV_hub(i),S1(i),0,1);
 P1_FREEV_hub(i) = P;
 T1_FREEV_hub(i) = T;
 Cp1_FREEV_hub(i) = Cp;
 rho1_FREEV_hub(i) = rho;
 Visc1_FREEV_hub(i) = Visc;
 kappa1_FREEV_hub(i) = kappa;
 a1_FREEV_hub(i) = a;

 MW1_FREEV_hub(i) = W1_FREEV_hub(i)/a1_FREEV_hub(i); % Station 1 relative
Mach FREEV_hub

 MCm1_FREEV_hub(i) = Cm1_FREEV_hub(i)/a1_FREEV_hub(i); % Relative inlet
meridional Mach FREEV_hub

 %######## at the Tip

 H1_FREEV_tip(i) = H01(i)-(C1_FREEV_tip(i)^2)/2; % Static enthalpy at rotor
inlet FREEV

 [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H1_FREEV_tip(i),S1(i),0,1);
 P1_FREEV_tip(i) = P;
 T1_FREEV_tip(i) = T;
 Cp1_FREEV_tip(i) = Cp;
 rho1_FREEV_tip(i) = rho;
 Visc1_FREEV_tip(i) = Visc;
 kappa1_FREEV_tip(i) = kappa;
 a1_FREEV_tip(i) = a;

 MW1_FREEV_tip(i) = W1_FREEV_tip(i)/a1_FREEV_tip(i); % Station 1 relative
Mach FREEV_tip

 MCm1_FREEV_tip(i) = Cm1_FREEV_tip(i)/a1_FREEV_tip(i); % Relative inlet
meridional Mach FREEV_tip

 %############## Station 1 General Whirl Distribution relative properties
##############

%######### at the Hub
```

```
H01_rel_FREEV_hub(i) = H1_FREEV_hub(i)+ (W1_FREEV_hub(i)^2)/2; % Relative
total enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H01_rel_FREEV_hub(i),S1(i),0,1);
P01_rel_FREEV_hub(i) = P;
T01_rel_FREEV_hub(i) = T;

I1_FREEV_hub(i) = H1_FREEV_hub(i)+(W1_FREEV_hub(i)^2)/2-
(U1_FREEV_hub(i)^2)/2; % Station 1 rothalpy at the hub

%####### at the Tip

H01_rel_FREEV_tip(i) = H1_FREEV_tip(i)+ (W1_FREEV_tip(i)^2)/2; % Relative
total enthalpy at the tip
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H01_rel_FREEV_tip(i),S1(i),0,1);
P01_rel_FREEV_tip(i) = P;
T01_rel_FREEV_tip(i) = T;

I1_FREEV_tip(i) = H1_FREEV_tip(i)+(W1_FREEV_tip(i)^2)/2-
(U1_FREEV_tip(i)^2)/2; % Station 1 rothalpy at the tip

%############ Station 1 Reaction variation across the radius #############


if n==-1
    REACT1_FREEV_hub(i)=1-(1-REACT(i))/((r_hub_rtr(i)/r_rms_1(i))^2);
    REACT1_FREEV_tip(i)=1-(1-REACT(i))/((r_tip_rtr(i)/r_rms_1(i))^2);
    elseif n==0
            REACT1_FREEV_hub(i)=1+(1-REACT(i))*(1-
2/(r_hub_rtr(i)/r_rms_1(i)));
            REACT1_FREEV_tip(i)=1+(1-REACT(i))*(1-
2/(r_tip_rtr(i)/r_rms_1(i)));
            elseif n==1
                REACT1_FREEV_hub(i)=1-(1-REACT(i))*(1-
2*log(r_hub_rtr(i)/r_rms_1(i)));
                REACT1_FREEV_tip(i)=1-(1-REACT(i))*(1-
2*log(r_tip_rtr(i)/r_rms_1(i)));
end



%###########à#########################################################
%###################### Station 2 General Whirl Distribution #########
%####################################################################



%#### C_theta2 General Whirl Distribution
C_theta2_FREEV_hub(i)=aa(i)*(r_hub_2(i)/r_rms_2(i))^(n)+bb(i)/(r_hub_2(i)/r
_rms_2(i));
C_theta2_FREEV_tip(i)=aa(i)*(r_tip_2(i)/r_rms_2(i))^(n)+bb(i)/(r_tip_2(i)/r
_rms_2(i));

%#### Cm2 General Whirl Distribution
if n==-1
     Cm2_FREEV_hub(i)=Cm2(i);
     Cm2_FREEV_tip(i)=Cm2(i);
     elseif n==0
```

```
       Cm2_FREEV_hub(i)=sqrt(Cm2(i)^2-
(2*(aa(i)^2*log(r_hub_2(i)/r_rms_2(i))-
aa(i)*bb(i)*(1/(r_hub_2(i)/r_rms_2(i))-1))));
       Cm2_FREEV_tip(i)=sqrt(Cm2(i)^2-
(2*(aa(i)^2*log(r_tip_2(i)/r_rms_2(i))-
aa(i)*bb(i)*(1/(r_tip_2(i)/r_rms_2(i))-1))));
       elseif n==1
         Cm2_FREEV_hub(i)=sqrt(Cm2(i)^2-
4*aa(i)*bb(i)*log(r_hub_2(i)/r_rms_2(i))-
2*(aa(i)^2)*((r_hub_2(i)/r_rms_2(i))^2-1));
         Cm2_FREEV_tip(i)=sqrt(Cm2(i)^2-
4*aa(i)*bb(i)*log(r_tip_2(i)/r_rms_2(i))-
2*(aa(i)^2)*((r_tip_2(i)/r_rms_2(i))^2-1));
end


 %W2_FREEV_hub
 U2_FREEV_hub(i)=r_hub_2(i)*pi*RPM/30;

 W_theta2_FREEV_hub(i) = U2_FREEV_hub(i)-C_theta2_FREEV_hub(i);
 Beta2_FREEV_hub(i) = atand(W_theta2_FREEV_hub(i)/Cm2_FREEV_hub(i));
 W2_FREEV_hub(i) = Cm2_FREEV_hub(i)/cosd(Beta2_FREEV_hub(i));

 %C2_FREEV_hub
 C2_FREEV_hub(i) = (Cm2_FREEV_hub(i)^2+C_theta2_FREEV_hub(i)^2)^0.5;
 Alpha2_FREEV_hub(i) = atand(C_theta2_FREEV_hub(i)/Cm2_FREEV_hub(i));


 %W2_FREEV_tip
 U2_FREEV_tip(i)=r_tip_2(i)*pi*RPM/30;

 W_theta2_FREEV_tip(i) = U2_FREEV_tip(i)-C_theta2_FREEV_tip(i);
 Beta2_FREEV_tip(i) = atand(W_theta2_FREEV_tip(i)/Cm2_FREEV_tip(i));
 W2_FREEV_tip(i) = Cm2_FREEV_tip(i)/cosd(Beta2_FREEV_tip(i));

 %C2_free_tip
 C2_FREEV_tip(i) = (Cm2_FREEV_tip(i)^2+C_theta2_FREEV_tip(i)^2)^0.5;
 Alpha2_FREEV_tip(i) = atand(C_theta2_FREEV_tip(i)/Cm2_FREEV_tip(i));

 W2onW1_hub(i)=W2_FREEV_hub(i)/W1_FREEV_hub(i);
 W2onW1_tip(i)=W2_FREEV_tip(i)/W1_FREEV_tip(i);
%########## Station 2 General Whirl Distribution  static properties
###########

%##### at the hub

S2(i) = S1(i)+dS21(i);

I2_FREEV_hub(i) = I1_FREEV_hub(i); %I.e. constant rothalpy through a rotor

H2_FREEV_hub(i) = I2_FREEV_hub(i)-
(W2_FREEV_hub(i)^2)/2+(U2_FREEV_hub(i)^2)/2;

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] = state('HS',
H2_FREEV_hub(i),S2(i),0,1);
P2_FREEV_hub(i) = P;
T2_FREEV_hub(i) = T;
Cp2_FREEV_hub(i) = Cp;
```

```
rho2_FREEV_hub(i) = rho;
Visc2_FREEV_hub(i) = Visc;
kappa2_FREEV_hub(i) = kappa;
a2_FREEV_hub(i) = a;

MC2_FREEV_hub(i) = C2_FREEV_hub(i)/a2_FREEV_hub(i); % Absolute inlet Mach
FREEV_hub#

MCm2_FREEV_hub(i) = Cm2_FREEV_hub(i)/a2_FREEV_hub(i); % Relative inlet
meridional Mach FREEV_hub#

%#### at the tip
S2(i) = S1(i)+dS21(i);

I2_FREEV_tip(i) = I1_FREEV_tip(i); %I.e. constant rothalpy through a rotor

H2_FREEV_tip(i) = I2_FREEV_tip(i)-
(W2_FREEV_tip(i)^2)/2+(U2_FREEV_tip(i)^2)/2;

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] =
state('HS',H2_FREEV_tip(i),S2(i),0,1);
P2_FREEV_tip(i) = P;
T2_FREEV_tip(i) = T;
Cp2_FREEV_tip(i) = Cp;
rho2_FREEV_tip(i) = rho;
Visc2_FREEV_tip(i) = Visc;
kappa2_FREEV_tip(i) = kappa;
a2_FREEV_tip(i) = a;

MC2_FREEV_tip(i) = C2_FREEV_tip(i)/a2_FREEV_tip(i); % Absolute inlet Mach
FREEV_tip

MCm2_FREEV_tip(i) = Cm2_FREEV_tip(i)/a2_FREEV_tip(i); % Relative inlet
meridional Mach FREEV_tip



%############# Station 2 General Whirl Distribution relative properties
##############

%##### at the hub

H02_rel_FREEV_hub(i) = H2_FREEV_hub(i)+ (W2_FREEV_hub(i)^2)/2; % Relative
total enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H02_rel_FREEV_hub(i),S2(i),0,1);
P02_rel_FREEV_hub(i) = P;
T02_rel_FREEV_hub(i) = T;


%##### at the tip

H02_rel_FREEV_tip(i) = H2_FREEV_tip(i)+ (W2_FREEV_tip(i)^2)/2; % Relative
total enthalpy
```

```
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H02_rel_FREEV_tip(i),S2(i),0,1);
P02_rel_FREEV_tip(i) = P;
T02_rel_FREEV_tip(i) = T;

%########### Station 2 General Whirl Distribution total properties
###########

%##### at the hub

H02_FREEV_hub(i) = H2_FREEV_hub(i)+(C2_FREEV_hub(i)^2)/2; % Exit total
enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] =
state('HS',H02_FREEV_hub(i),S2(i),0,1);
P02_FREEV_hub(i) = P;
T02_FREEV_hub(i) = T;

%##### at the tip

H02_FREEV_tip(i) = H2_FREEV_tip(i)+(C2_FREEV_tip(i)^2)/2; % Exit total
enthalpy
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He] =
state('HS',H02_FREEV_tip(i),S2(i),0,1);
P02_FREEV_tip(i) = P;
T02_FREEV_tip(i) = T;

%######## deHaller number Free Vortex law rtr

%##### at the hub
dH_rtr_FREEV_hub(i)=W2_FREEV_hub(i)/W1_FREEV_hub(i);

%#### at the tip
dH_rtr_FREEV_tip(i)=W2_FREEV_tip(i)/W1_FREEV_tip(i);

%##################################################
%###########Station 3 General Whirl Distribution##
%##################################################

%#### C_theta3 FREE VORTEX LAW
C_theta3_FREEV_hub(i)=aa(i)*(r_hub_3(i)/r_rms_3(i))^(n)-
bb(i)/(r_hub_3(i)/r_rms_3(i));
C_theta3_FREEV_tip(i)=aa(i)*(r_tip_3(i)/r_rms_3(i))^(n)-
bb(i)/(r_tip_3(i)/r_rms_3(i));

%#### Cm3 FREE VORTEX LAW

if n==-1
%      Cm3_FREEV_hub
     Cm3_FREEV_hub(i)=Cm3(i);
%      Cm1_FREEV_tip
     Cm3_FREEV_tip(i)=Cm3(i);
     elseif n==0
%          Cm3_FREEV_hub
         Cm3_FREEV_hub(i)=sqrt(Cm3(i)^2-
(2*(aa(i)^2*log(r_hub_3(i)/r_rms_3(i))+aa(i)*bb(i)*(1/(r_hub_3(i)/r_rms_3(i
))-1))));
```

```
%          Cm3_FREEV_tip
         Cm3_FREEV_tip(i)=sqrt(Cm3(i)^2-
(2*(aa(i)^2*log(r_tip_3(i)/r_rms_3(i))+aa(i)*bb(i)*(1/(r_tip_3(i)/r_rms_3(i
))-1))));
         elseif n==1
%           Cm3_FREEV_hub

Cm3_FREEV_hub(i)=sqrt(Cm3(i)^2+(4*aa(i)*bb(i)*log(r_hub_3(i)/r_rms_3(i))-
2*aa(i)^2*((r_hub_3(i)/r_rms_3(i))^2-1)));
%           Cm3_FREEV_tip

Cm3_FREEV_tip(i)=sqrt(Cm3(i)^2+(4*aa(i)*bb(i)*log(r_tip_3(i)/r_rms_3(i))-
2*aa(i)^2*((r_tip_3(i)/r_rms_3(i))^2-1)));

end

% C and U FREE VORTEX

Alpha3_FREEV_hub(i) = atand(C_theta3_FREEV_hub(i)/Cm3_FREEV_hub(i));
C3_FREEV_hub(i) = Cm3_FREEV_hub(i)/cosd(Alpha3_FREEV_hub(i));
U3_FREEV_hub(i)=r_hub_3(i)*pi*RPM/30;

Alpha3_FREEV_tip(i) = atand(C_theta3_FREEV_tip(i)/Cm3_FREEV_tip(i));
C3_FREEV_tip(i) = Cm3_FREEV_tip(i)/cosd(Alpha3_FREEV_tip(i));
U3_FREEV_tip(i)=r_tip_3(i)*pi*RPM/30;
C3onC2_hub(i)=C3_FREEV_hub(i)/C2_FREEV_hub(i);
C3onC2_tip(i)=C3_FREEV_tip(i)/C2_FREEV_tip(i);
Cm1onU1_hub(i)=Cm1_FREEV_hub(i)/U1(i);
Cm1onU1_tip(i)=Cm1_FREEV_tip(i)/U1(i);
Cm2onU2_hub(i)=Cm2_FREEV_hub(i)/U2(i);
Cm2onU2_tip(i)=Cm2_FREEV_tip(i)/U2(i);
W1onU1_hub(i)= W1_FREEV_hub(i)/U1(i);
W1onU1_tip(i)= W1_FREEV_tip(i)/U1(i);
W2onU1_hub(i)= W2_FREEV_hub(i)/U1(i);
W2onU1_tip(i)= W2_FREEV_tip(i)/U1(i);


%########### Station 3 General Whirl Distribution static properties
##########

%#### HUB

H03_FREEV_hub(i) = H02_FREEV_hub(i); % Constant total enthalpy through the
stator
H3_FREEV_hub(i) = H03_FREEV_hub(i)-(C3_FREEV_hub(i)^2)/2;
S3(i) = S2(i)+dS32(i);
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H3_FREEV_hub(i),S3(i),0,1);
P3_FREEV_hub(i) = P;
T3_FREEV_hub(i) = T;
Cp3_FREEV_hub(i) = Cp;
rho3_FREEV_hub(i) = rho;
Visc3_FREEV_hub(i) = Visc;
kappa3_FREEV_hub(i) = kappa;
a3_FREEV_hub(i) = a;

MC3_FREEV_hub(i) = C3_FREEV_hub(i)/a3_FREEV_hub(i);% Absolute inlet Mach
FREEV_hub #
```

```
MCm3_FREEV_hub(i) = Cm3_FREEV_hub(i)/a3_FREEV_hub(i);% Relative inlet
meridional Mach FREEV_hub #

%#### TIP

H03_FREEV_tip(i) = H02_FREEV_tip(i); % Constant total enthalpy through the
stator
H3_FREEV_tip(i) = H03_FREEV_tip(i)-(C3_FREEV_tip(i)^2)/2;
S3(i) = S2(i)+dS32(i);
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H3_FREEV_tip(i),S3(i),0,1);
P3_FREEV_tip(i) = P;
T3_FREEV_tip(i) = T;
Cp3_FREEV_tip(i) = Cp;
rho3_FREEV_tip(i) = rho;
Visc3_FREEV_tip(i) = Visc;
kappa3_FREEV_tip(i) = kappa;
a3_FREEV_tip(i) = a;

MC3_FREEV_tip(i) = C3_FREEV_hub(i)/a3_FREEV_hub(i);% Absolute inlet Mach
FREEV_hub #

MCm3_FREEV_tip(i) = Cm3_FREEV_hub(i)/a3_FREEV_hub(i);% Relative inlet
meridional Mach FREEV_hub #

%############ Station 3 General Whirl Distribution total properties
##########

%#### HUB
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H03_FREEV_hub(i),S3(i),0,1);
P03_FREEV_hub(i) = P;
T03_FREEV_hub(i) = T;

%#### TIP

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('HS',H03_FREEV_tip(i),S3(i),0,1);
P03_FREEV_tip(i) = P;
T03_FREEV_tip(i) = T;

%######## deHaller number Forced Vortex law str
%#### at the hub
dH_str_FREEV_hub(i) = C3_FREEV_hub(i)/C2_FREEV_hub(i);

%####at the tip
dH_str_FREEV_tip(i) = C3_FREEV_tip(i)/C2_FREEV_tip(i);
```

```
%######################################################################
%##     Blade angles and diffusion factor from Forced Vortex law      ##
%##     for the compressor stages                                      ##
%######################################################################



%#############   Rotor angles Forced vortex law

%#### at the HUB

diameter_rtr_hub(i)=2*pi*r_hub_rtr(i);
spacing_rtr_hub(i)=diameter_rtr_hub(i)/numb_blades_rtr(i);
SONC_rtr_FV_hub(i)=spacing_rtr_hub(i)/chord_rtr(i);
TONC_rtr_hub(i)=TONC_rtr(i)*1.5;

rel_ang_in = Beta1_FV_hub(i);
rel_ang_out = Beta2_FV_hub(i);
SONC = SONC_rtr_FV_hub(i);
TONC=TONC_rtr_hub(i);
M = MW1_FV_hub(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_rtr_FV_hub(i) = incidence_angle;
deviation_angle_rtr_FV_hub(i) = deviation_angle;
camber_angle_rtr_FV_hub(i) = camber_angle;
attack_angle_rtr_FV_hub(i) = attack_angle;
stagger_angle_rtr_FV_hub(i) = stagger_angle;
blade_angle_in_rtr_FV_hub(i) = blade_angle_in;
blade_angle_out_rtr_FV_hub(i) = blade_angle_out;

%#### at the TIP

diameter_rtr_tip(i)=2*pi*r_tip_rtr(i);
spacing_rtr_tip(i)=diameter_rtr_tip(i)/numb_blades_rtr(i);
SONC_rtr_FV_tip(i)=spacing_rtr_tip(i)/chord_rtr(i);
TONC_rtr_tip(i)=TONC_rtr(i)*0.5;

rel_ang_in = Beta1_FV_tip(i);
rel_ang_out = Beta2_FV_tip(i);
SONC = SONC_rtr_FV_tip(i);
TONC =TONC_rtr_tip(i);
M = MW1_FV_tip(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_rtr_FV_tip(i) = incidence_angle;
deviation_angle_rtr_FV_tip(i) = deviation_angle;
camber_angle_rtr_FV_tip(i) = camber_angle;
attack_angle_rtr_FV_tip(i) = attack_angle;
stagger_angle_rtr_FV_tip(i) = stagger_angle;
blade_angle_in_rtr_FV_tip(i) = blade_angle_in;
blade_angle_out_rtr_FV_tip(i) = blade_angle_out;

%################ Stator angles Forced Vortex law

%#### at the HUB
```

```
diameter_str_hub(i)=2*pi*r_hub_str(i);
spacing_str_hub(i)=diameter_str_hub(i)/numb_blades_str(i);
SONC_str_FV_hub(i)=spacing_str_hub(i)/chord_str(i);

rel_ang_in = Alpha2_FV_hub(i);
rel_ang_out = Alpha3_FV_hub(i);
SONC = SONC_str_FV_hub(i);
TONC = TONC_str(i);
M = MC2_FV_hub(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_str_FV_hub(i) = incidence_angle;
deviation_angle_str_FV_hub(i) = deviation_angle;
camber_angle_str_FV_hub(i) = camber_angle;
attack_angle_str_FV_hub(i) = attack_angle;
stagger_angle_str_FV_hub(i) = stagger_angle;
blade_angle_in_str_FV_hub(i) = blade_angle_in;
blade_angle_out_str_FV_hub(i) = blade_angle_out;


%#### at the TIP

diameter_str_tip(i)=2*pi*r_tip_str(i);
spacing_str_tip(i)=diameter_str_tip(i)/numb_blades_str(i);
SONC_str_FV_tip(i)=spacing_str_tip(i)/chord_str(i);

rel_ang_in = Alpha2_FV_tip(i);
rel_ang_out = Alpha3_FV_tip(i);
SONC = SONC_str_FV_tip(i);
TONC = TONC_str(i);
M = MC2_FV_tip(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_str_FV_tip(i) = incidence_angle;
deviation_angle_str_FV_tip(i) = deviation_angle;
camber_angle_str_FV_tip(i) = camber_angle;
attack_angle_str_FV_tip(i) = attack_angle;
stagger_angle_str_FV_tip(i) = stagger_angle;
blade_angle_in_str_FV_tip(i) = blade_angle_in;
blade_angle_out_str_FV_tip(i) = blade_angle_out;

%############### Rotor diffusion factors Forced Vortex Law ############

%#### HUB

rel_ang_in = Beta1_FV_hub(i);
rel_ang_out = Beta2_FV_hub(i);

[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm1_FV_hub(i),Cm2_FV_hub(i),r_hub_1(i),r_h
ub_2(i),SONC_rtr_FV_hub(i),TONC_rtr_hub(i),AVDR_rtr(i),MCm1_FV_hub(i));
DF_lbl_rtr_FV_hub(i) = DF_lbl;
Deq_star_lbl_rtr_FV_hub(i) = Deq_star_lbl;
Deq_rtr_FV_hub(i) = Deq;
Deq_star_ks_rtr_FV_hub(i) = Deq_star_ks;
```

```
[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm1_FV_hub(i),SONC_rtr_FV_hub(i),TONC_rtr_hub
(i),kappa1_FV_hub(i));
Mcrit_Hearsey_rtr_FV_hub(i) = Mcrit_Hearsey;
Mcrit_Sch_rtr_FV_hub(i) = Mcrit_Sch;

%#### TIP

rel_ang_in = Beta1_FV_tip(i);
rel_ang_out = Beta2_FV_tip(i);


[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm1_FV_tip(i),Cm2_FV_tip(i),r_tip_1(i),r_t
ip_2(i),SONC_rtr_FV_tip(i),TONC_rtr_tip(i),AVDR_rtr(i),MCm1_FV_tip(i));
DF_lbl_rtr_FV_tip(i) = DF_lbl;
Deq_star_lbl_rtr_FV_tip(i) = Deq_star_lbl;
Deq_rtr_FV_tip(i) = Deq;
Deq_star_ks_rtr_FV_tip(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm1_FV_tip(i),SONC_rtr_FV_tip(i),TONC_rtr_tip
(i),kappa1_FV_tip(i));
Mcrit_Hearsey_rtr_FV_tip(i) = Mcrit_Hearsey;
Mcrit_Sch_rtr_FV_tip(i) = Mcrit_Sch;


%############### Stator diffusion factors Forced Vortex Law ############

%#### HUB

rel_ang_in = Alpha2_FV_hub(i);
rel_ang_out = Alpha3_FV_hub(i);

[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm2_FV_hub(i),Cm3_FV_hub(i),r_hub_2(i),r_h
ub_3(i),SONC_str_FV_hub(i),TONC_str(i),AVDR_str(i),MCm2_FV_hub(i));
DF_lbl_str_FV_hub(i) = DF_lbl;
Deq_star_lbl_str_FV_hub(i) = Deq_star_lbl;
Deq_str_FV_hub(i) = Deq;
Deq_star_ks_str_FV_hub(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm2_FV_hub(i),SONC_str_FV_hub(i),TONC_str(i),
kappa2_FV_hub(i));
Mcrit_Hearsey_str_FV_hub(i) = Mcrit_Hearsey;
Mcrit_Sch_str_FV_hub(i) = Mcrit_Sch;

%#### TIP

rel_ang_in = Alpha2_FV_tip(i);
rel_ang_out = Alpha3_FV_tip(i);

[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm2_FV_tip(i),Cm3_FV_tip(i),r_tip_2(i),r_t
ip_3(i),SONC_str_FV_tip(i),TONC_str(i),AVDR_str(i),MCm2_FV_tip(i));
DF_lbl_str_FV_tip(i) = DF_lbl;
Deq_star_lbl_str_FV_tip(i) = Deq_star_lbl;
Deq_str_FV_tip(i) = Deq;
```

```
Deq_star_ks_str_FV_tip(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm2_FV_tip(i),SONC_str_FV_tip(i),TONC_str(i),
kappa2_FV_tip(i));
Mcrit_Hearsey_str_FV_tip(i) = Mcrit_Hearsey;
Mcrit_Sch_str_FV_tip(i) = Mcrit_Sch;


%#######################################################################
%##               Blade angles and diffusion factor from              ##
%##                    General Whirl Distribution                     ##
%##                   for the compressor stages                       ##
%#######################################################################


%#############   Rotor angles Modified Free vortex law

%#### at the HUB

diameter_rtr_hub(i)=2*pi*r_hub_rtr(i);
spacing_rtr_hub(i)=diameter_rtr_hub(i)/numb_blades_rtr(i);
SONC_rtr_FREEV_hub(i)=spacing_rtr_hub(i)/chord_rtr(i);
TONC_rtr_hub(i)=TONC_rtr(i)*1.5;

rel_ang_in = Beta1_FREEV_hub(i);
rel_ang_out = Beta2_FREEV_hub(i);
SONC = SONC_rtr_FREEV_hub(i);
TONC=TONC_rtr_hub(i);
M = MW1_FREEV_hub(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_rtr_FREEV_hub(i) = incidence_angle;
deviation_angle_rtr_FREEV_hub(i) = deviation_angle;
camber_angle_rtr_FREEV_hub(i) = camber_angle;
attack_angle_rtr_FREEV_hub(i) = attack_angle;
stagger_angle_rtr_FREEV_hub(i) = stagger_angle;
blade_angle_in_rtr_FREEV_hub(i) = blade_angle_in;
blade_angle_out_rtr_FREEV_hub(i) = blade_angle_out;

%#### at the TIP

diameter_rtr_tip(i)=2*pi*r_tip_rtr(i);
spacing_rtr_tip(i)=diameter_rtr_tip(i)/numb_blades_rtr(i);
SONC_rtr_FREEV_tip(i)=spacing_rtr_tip(i)/chord_rtr(i);
TONC_rtr_tip(i)=TONC_rtr(i)*0.5;

rel_ang_in = Beta1_FREEV_tip(i);
rel_ang_out = Beta2_FREEV_tip(i);
SONC = SONC_rtr_FREEV_tip(i);
TONC =TONC_rtr_tip(i);
M = MW1_FREEV_tip(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_rtr_FREEV_tip(i) = incidence_angle;
deviation_angle_rtr_FREEV_tip(i) = deviation_angle;
camber_angle_rtr_FREEV_tip(i) = camber_angle;
attack_angle_rtr_FREEV_tip(i) = attack_angle;
```

```
stagger_angle_rtr_FREEV_tip(i) = stagger_angle;
blade_angle_in_rtr_FREEV_tip(i) = blade_angle_in;
blade_angle_out_rtr_FREEV_tip(i) = blade_angle_out;

%################ Stator angles Modified Free Vortex law

%#### at the HUB

diameter_str_hub(i)=2*pi*r_hub_str(i);
spacing_str_hub(i)=diameter_str_hub(i)/numb_blades_str(i);
SONC_str_FREEV_hub(i)=spacing_str_hub(i)/chord_str(i);

rel_ang_in = Alpha2_FREEV_hub(i);
rel_ang_out = Alpha3_FREEV_hub(i);
SONC = SONC_str_FREEV_hub(i);
TONC = TONC_str(i);
M = MC2_FREEV_hub(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_str_FREEV_hub(i) = incidence_angle;
deviation_angle_str_FREEV_hub(i) = deviation_angle;
camber_angle_str_FREEV_hub(i) = camber_angle;
attack_angle_str_FREEV_hub(i) = attack_angle;
stagger_angle_str_FREEV_hub(i) = stagger_angle;
blade_angle_in_str_FREEV_hub(i) = blade_angle_in;
blade_angle_out_str_FREEV_hub(i) = blade_angle_out;


%#### at the TIP

diameter_str_tip(i)=2*pi*r_tip_str(i);
spacing_str_tip(i)=diameter_str_tip(i)/numb_blades_str(i);
SONC_str_FREEV_tip(i)=spacing_str_tip(i)/chord_str(i);

rel_ang_in = Alpha2_FREEV_tip(i);
rel_ang_out = Alpha3_FREEV_tip(i);
SONC = SONC_str_FREEV_tip(i);
TONC = TONC_str(i);
M = MC2_FREEV_tip(i);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,bl
ade_angle_in,blade_angle_out] =
Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_str_FREEV_tip(i) = incidence_angle;
deviation_angle_str_FREEV_tip(i) = deviation_angle;
camber_angle_str_FREEV_tip(i) = camber_angle;
attack_angle_str_FREEV_tip(i) = attack_angle;
stagger_angle_str_FREEV_tip(i) = stagger_angle;
blade_angle_in_str_FREEV_tip(i) = blade_angle_in;
blade_angle_out_str_FREEV_tip(i) = blade_angle_out;

%############### Rotor diffusion factors Modified Free Vortex Law
############

%#### HUB

rel_ang_in = Beta1_FREEV_hub(i);
rel_ang_out = Beta2_FREEV_hub(i);
```

```
[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm1_FREEV_hub(i),Cm2_FREEV_hub(i),r_hub_1(
i),r_hub_2(i),SONC_rtr_FREEV_hub(i),TONC_rtr_hub(i),AVDR_rtr(i),MCm1_FREEV_
hub(i));
DF_lbl_rtr_FREEV_hub(i) = DF_lbl;
Deq_star_lbl_rtr_FREEV_hub(i) = Deq_star_lbl;
Deq_rtr_FREEV_hub(i) = Deq;
Deq_star_ks_rtr_FREEV_hub(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm1_FREEV_hub(i),SONC_rtr_FREEV_hub(i),TONC_r
tr_hub(i),kappa1_FREEV_hub(i));
Mcrit_Hearsey_rtr_FREEV_hub(i) = Mcrit_Hearsey;
Mcrit_Sch_rtr_FREEV_hub(i) = Mcrit_Sch;

%#### TIP

rel_ang_in = Beta1_FREEV_tip(i);
rel_ang_out = Beta2_FREEV_tip(i);



[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm1_FREEV_tip(i),Cm2_FREEV_tip(i),r_tip_1(
i),r_tip_2(i),SONC_rtr_FREEV_tip(i),TONC_rtr_tip(i),AVDR_rtr(i),MCm1_FREEV_
tip(i));
DF_lbl_rtr_FREEV_tip(i) = DF_lbl;
Deq_star_lbl_rtr_FREEV_tip(i) = Deq_star_lbl;
Deq_rtr_FREEV_tip(i) = Deq;
Deq_star_ks_rtr_FREEV_tip(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm1_FREEV_tip(i),SONC_rtr_FREEV_tip(i),TONC_r
tr_tip(i),kappa1_FREEV_tip(i));
Mcrit_Hearsey_rtr_FREEV_tip(i) = Mcrit_Hearsey;
Mcrit_Sch_rtr_FREEV_tip(i) = Mcrit_Sch;

%############### Stator diffusion factors Free Vortex Law ############

%#### HUB

rel_ang_in = Alpha2_FREEV_hub(i);
rel_ang_out = Alpha3_FREEV_hub(i);

[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm2_FREEV_hub(i),Cm3_FREEV_hub(i),r_hub_2(
i),r_hub_3(i),SONC_str_FREEV_hub(i),TONC_str(i),AVDR_str(i),MCm2_FREEV_hub(
i));
DF_lbl_str_FREEV_hub(i) = DF_lbl;
Deq_star_lbl_str_FREEV_hub(i) = Deq_star_lbl;
Deq_str_FREEV_hub(i) = Deq;
Deq_star_ks_str_FREEV_hub(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm2_FREEV_hub(i),SONC_str_FREEV_hub(i),TONC_s
tr(i),kappa2_FREEV_hub(i));
Mcrit_Hearsey_str_FREEV_hub(i) = Mcrit_Hearsey;
Mcrit_Sch_str_FREEV_hub(i) = Mcrit_Sch;

%#### TIP
```

```
rel_ang_in = Alpha2_FREEV_tip(i);
rel_ang_out = Alpha3_FREEV_tip(i);

[DF_lbl,Deq_star_lbl,Deq,Deq_star_ks] =
Deq_star1(rel_ang_in,rel_ang_out,Cm2_FREEV_tip(i),Cm3_FREEV_tip(i),r_tip_2(
i),r_tip_3(i),SONC_str_FREEV_tip(i),TONC_str(i),AVDR_str(i),MCm2_FREEV_tip(
i));
DF_lbl_str_FREEV_tip(i) = DF_lbl;
Deq_star_lbl_str_FREEV_tip(i) = Deq_star_lbl;
Deq_str_FREEV_tip(i) = Deq;
Deq_star_ks_str_FREEV_tip(i) = Deq_star_ks;

[Mcrit_Hearsey,Mcrit_Sch] =
MCRIT1(rel_ang_in,rel_ang_out,Cm2_FREEV_tip(i),SONC_str_FREEV_tip(i),TONC_s
tr(i),kappa2_FREEV_tip(i));
Mcrit_Hearsey_str_FREEV_tip(i) = Mcrit_Hearsey;
Mcrit_Sch_str_FREEV_tip(i) = Mcrit_Sch;
```

B3, Blade shape plot

```
%####################################################################
%##                                                                ##
%##                       Blade shape plot                         ##
%##                                                                ##
%##                     Daniele Perrotti 2013                      ##
%##                                                                ##
%##            Lund University/Dept of Energy Sciences             ##
%##                                                                ##
%####################################################################


globalvariables
global  i chord_rtr



%#################### rotor ################################

theta_rtr(i)= STG(i).camber_angle_rtr;
stagger_rtr(i)= STG(i).stagger_angle_rtr;
chord_rtr(i)= STG(i).chord_rtr;
tb_rtr(i)=STG(i).TONC_rtr.*chord_rtr(i);
r_0_rtr(i)=0.1.*tb_rtr(i);

%radius of curvature
R_c_rtr(i)=chord_rtr(i)*1./(2*sind(theta_rtr(i)./2));

%origin of curvature
orig_c_rtr(i)=-R_c_rtr(i)*cosd(theta_rtr(i)./2);
```

```
if i==1

    x_c_rtr1=[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2)];
    nn1=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
else

    nn=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
    x_c_rtr1=[x_c_rtr1;[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2),zeros(1,nn1-
nn)]];
end

clear x_c_rtr
if i==1
    nn=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
end
    x_c_rtr=x_c_rtr1(i,1:nn);



% behaviour of chord in y direction
y_c_rtr(i,1:nn)=orig_c_rtr(i)+sqrt(R_c_rtr(i)^2-x_c_rtr.^2);
%staggered blade
x_c_s_rtr(i,1:nn)=x_c_rtr.*cosd(stagger_rtr(i))+y_c_rtr(i,1:nn).*sind(stagg
er_rtr(i));
y_c_s_rtr(i,1:nn)=x_c_rtr.*sind(stagger_rtr(i))-
y_c_rtr(i,1:nn).*cosd(stagger_rtr(i));


figure(i+1)
hold on
%chord plot
plot(y_c_s_rtr(i,1:nn),x_c_s_rtr(i,1:nn),'--r')

plot(y_c_s_rtr(i,1:nn)+spacing_rtr(i),x_c_s_rtr(i,1:nn),'--r')
plot(y_c_s_rtr(i,1:nn)-spacing_rtr(i),x_c_s_rtr(i,1:nn),'--r')




%    axis([-0.09 0.09 -0.09 0.09])

%#########    suction surface
%camberline coordinate at origin of the chord

y_orig_rtr(i)=(chord_rtr(i)./2).*tand(theta_rtr(i)./4);




dd_rtr(i)=y_orig_rtr(i)+tb_rtr(i)./2-r_0_rtr(i).*sind(theta_rtr(i)./2);
%radius of curvature
Rup_rtr(i)=(dd_rtr(i).^2-r_0_rtr(i).^2+(chord_rtr(i)./2-
r_0_rtr(i).*cosd(theta_rtr(i)./2)).^2)/(2.*(dd_rtr(i)-r_0_rtr(i)));


x_u_rtr_int1(i)=-(chord_rtr(i)./2-r_0_rtr(i).*cosd(theta_rtr(i)./2));
x_u_rtr_int2(i)=(chord_rtr(i)./2-r_0_rtr(i).*cosd(theta_rtr(i)./2));
```

```
if i==1

    x_u_rtr1=[(x_u_rtr_int1(i):0.001:x_u_rtr_int2(i))];
    nn1_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));

else

    nn_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));

x_u_rtr1=[x_u_rtr1;[(x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)),zeros(1,nn1_u-
nn_u)]];

end




clear x_u_rtr
if i==1
    nn_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));
end
    x_u_rtr=x_u_rtr1(i,1:nn_u);


y_u_orig_rtr(i,1:nn_u)=y_orig_rtr(i)+tb_rtr(i)/2-Rup_rtr(i);
% behaviour of suction surface in y direction
y_u_rtr(i,1:nn_u)=y_u_orig_rtr(i,1:nn_u)+sqrt(Rup_rtr(i)^2-x_u_rtr.^2);
%staggered blade
x_u_s_rtr(i,1:nn_u)=x_u_rtr*cosd(stagger_rtr(i))+y_u_rtr(i,1:nn_u)*sind(sta
gger_rtr(i));
y_u_s_rtr(i,1:nn_u)=x_u_rtr*sind(stagger_rtr(i))-
y_u_rtr(i,1:nn_u)*cosd(stagger_rtr(i));

% suction surface plot
 plot(y_u_s_rtr(i,1:nn_u),x_u_s_rtr(i,1:nn_u),'r')
 plot(y_u_s_rtr(i,1:nn_u)+spacing_rtr(i),x_u_s_rtr(i,1:nn_u),'r')
 plot(y_u_s_rtr(i,1:nn_u)-spacing_rtr(i),x_u_s_rtr(i,1:nn_u),'r')

 %########pressure surface

tb_l_rtr(i)=-tb_rtr(i);
r_0_l_rtr(i)=-r_0_rtr(i);
dd_l_rtr(i)=y_orig_rtr(i)+tb_l_rtr(i)/2-r_0_l_rtr(i)*sind(theta_rtr(i)/2);
Rlo_rtr(i)=(dd_l_rtr(i)^2-r_0_l_rtr(i)^2+(chord_rtr(i)/2-
r_0_l_rtr(i)*cosd(theta_rtr(i)/2))^2)/(2*(dd_l_rtr(i)-r_0_l_rtr(i)));

x_l_rtr_int1(i)=-(chord_rtr(i)/2-r_0_l_rtr(i)*cosd(theta_rtr(i)/2));
x_l_rtr_int2(i)=(chord_rtr(i)/2-r_0_l_rtr(i)*cosd(theta_rtr(i)/2));

if i==1

    x_l_rtr1=[(x_l_rtr_int1(i):0.001:x_l_rtr_int2(i))];
    nn1_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));

else

    nn_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));
```

```
x_l_rtr1=[x_l_rtr1;[(x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)),zeros(1,nn1_l-
nn_l)]];

end





clear x_l_rtr
if i==1
    nn_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));
end
    x_l_rtr=x_l_rtr1(i,1:nn_l);

y_l_orig_rtr(i,1:nn_l)=y_orig_rtr(i)+tb_l_rtr(i)/2-Rlo_rtr(i);
% behaviour of pressure surface in y direction
y_l_rtr(i,1:nn_l)=y_l_orig_rtr(i,1:nn_l)+sqrt(Rlo_rtr(i)^2-x_l_rtr.^2);
%staggered blade
x_l_s_rtr(i,1:nn_l)=x_l_rtr*cosd(stagger_rtr(i))+y_l_rtr(i,1:nn_l)*sind(sta
gger_rtr(i));
y_l_s_rtr(i,1:nn_l)=x_l_rtr*sind(stagger_rtr(i))-
y_l_rtr(i,1:nn_l)*cosd(stagger_rtr(i));





% pressure surface plot
plot(y_l_s_rtr(i,1:nn_l),x_l_s_rtr(i,1:nn_l),'r')
plot(y_l_s_rtr(i,1:nn_l)+spacing_rtr(i),x_l_s_rtr(i,1:nn_l),'r')
plot(y_l_s_rtr(i,1:nn_l)-spacing_rtr(i),x_l_s_rtr(i,1:nn_l),'r')



%nose design
y_n_rtr(i)=r_0_rtr(i)*sind(theta_rtr(i)/2);
x_n1_rtr(i)=-(chord_rtr(i)/2-r_0_rtr(i)*cosd(theta_rtr(i)/2));
x_n2_rtr(i)=chord_rtr(i)/2-r_0_rtr(i)*cosd(theta_rtr(i)/2);
ang1=0:0.001:2*pi;
xp_rtr=r_0_rtr(i).*cos(ang1);
yp_rtr=r_0_rtr(i).*sin(ang1);

x_n1_s_rtr(i)=x_n1_rtr(i)*cosd(stagger_rtr(i))+y_n_rtr(i)*sind(stagger_rtr(
i));
x_n2_s_rtr(i)=x_n2_rtr(i)*cosd(stagger_rtr(i))+y_n_rtr(i)*sind(stagger_rtr(
i));
y_n1_s_rtr(i)=x_n1_rtr(i)*sind(stagger_rtr(i))-
y_n_rtr(i)*cosd(stagger_rtr(i));
y_n2_s_rtr(i)=x_n2_rtr(i)*sind(stagger_rtr(i))-
y_n_rtr(i)*cosd(stagger_rtr(i));

%nose plot
plot(y_n1_s_rtr(i)+yp_rtr,x_n1_s_rtr(i)+xp_rtr,'r')
plot(y_n2_s_rtr(i)+yp_rtr,x_n2_s_rtr(i)+xp_rtr,'r')
plot(y_n1_s_rtr(i)+spacing_rtr(i)+yp_rtr,x_n1_s_rtr(i)+xp_rtr,'r')
plot(y_n1_s_rtr(i)-spacing_rtr(i)+yp_rtr,x_n1_s_rtr(i)+xp_rtr,'r')
plot(y_n2_s_rtr(i)+spacing_rtr(i)+yp_rtr,x_n2_s_rtr(i)+xp_rtr,'r')
plot(y_n2_s_rtr(i)-spacing_rtr(i)+yp_rtr,x_n2_s_rtr(i)+xp_rtr,'r')
```

```
%################stator########################

theta_str(i)=STG(i).camber_angle_str;
chord_str(i)=STG(i).chord_str;
stagger_str(i)=-STG(i).stagger_angle_str;
tb_str(i)=STG(i).TONC_str.*chord_str(i);
r_0_str(i)=0.1.*tb_str(i);


%radius of curvature
R_c_str(i)=chord_str(i)*1./(2*sind(theta_str(i)./2));

%origin of curvature
orig_c_str(i)=-R_c_str(i)*cosd(theta_str(i)./2);

%chord in x


if i==1

    x_c_str1=[(-chord_str(i)/2:0.001:chord_str(i)/2)];
    nn1s=length((-chord_str(i)/2:0.001:chord_str(i)/2));
else

    nns=length((-chord_str(i)/2:0.001:chord_str(i)/2));
    x_c_str1=[x_c_str1;[(-
chord_str(i)/2:0.001:chord_str(i)/2),zeros(1,nn1s-nns)]];
end

clear x_c_str
if i==1
    nns=length((-chord_str(i)/2:0.001:chord_str(i)/2));
end
    x_c_str=x_c_str1(i,1:nns);

% behaviour of chord in y direction
y_c_str(i,1:nns)=orig_c_str(i)+sqrt(R_c_str(i)^2-x_c_str.^2);
%staggered blade
x_c_s_str(i,1:nns)=x_c_str.*cosd(stagger_str(i))-
y_c_str(i,1:nns).*sind(stagger_str(i));% sign of y changed
y_c_s_str(i,1:nns)=x_c_str.*sind(stagger_str(i))+y_c_str(i,1:nns).*cosd(sta
gger_str(i));

%chord plot
axial_spc(i)=chord_rtr(i)*cosd(stagger_rtr(i))+0.2*(chord_rtr(i)*cosd(stagg
er_rtr(i)));
plot(y_c_s_str(i,1:nns),x_c_s_str(i,1:nns)-axial_spc(i),'--b')
plot(y_c_s_str(i,1:nns)+spacing_str(i),x_c_s_str(i,1:nns)-axial_spc(i),'--
b')
plot(y_c_s_str(i,1:nns)-spacing_str(i),x_c_s_str(i,1:nns)-axial_spc(i),'--
b')


%####suction surface

%camberline coordinate at origin of the chord
y_orig_str(i)=(chord_str(i)/2)*tand(theta_str(i)/4);
```

```
dd_str(i)=y_orig_str(i)+tb_str(i)/2-r_0_str(i)*sind(theta_str(i)/2);
Rup_str(i)=(dd_str(i)^2-r_0_str(i)^2+(chord_str(i)/2-
r_0_str(i)*cosd(theta_str(i)/2))^2)/(2*(dd_str(i)-r_0_str(i)));
theta_up_str(i)=2*asind(chord_str(i)/2-
r_0_str(i)*cosd(theta_str(i)/2))*(1/(Rup_str(i)-r_0_str(i)));

x_u_str_int1(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_u_str_int2(i)=(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));

if i==1

    x_u_str1=[(x_u_str_int1(i):0.001:x_u_str_int2(i))];
    nn1_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));

else

    nn_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));

x_u_str1=[x_u_str1;[(x_u_str_int1(i):0.001:x_u_str_int2(i)),zeros(1,nn1_us-
nn_us)]];

end

clear x_u_str
if i==1
    nn_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));
end
    x_u_str=x_u_str1(i,1:nn_us);


y_u_orig_str(i,1:nn_us)=y_orig_str(i)+tb_str(i)/2-Rup_str(i);

y_u_str(i,1:nn_us)=y_u_orig_str(i)+sqrt(Rup_str(i)^2-x_u_str.^2);
x_u_s_str(i,1:nn_us)=x_u_str*cosd(stagger_str(i))-
y_u_str(i,1:nn_us)*sind(stagger_str(i));
y_u_s_str(i,1:nn_us)=x_u_str*sind(stagger_str(i))+y_u_str(i,1:nn_us)*cosd(s
tagger_str(i));


% suction surface plot
plot(y_u_s_str(i,1:nn_us),x_u_s_str(i,1:nn_us)-axial_spc(i),'b')
plot(y_u_s_str(i,1:nn_us)+spacing_str(i),x_u_s_str(i,1:nn_us)-
axial_spc(i),'b')
plot(y_u_s_str(i,1:nn_us)-spacing_str(i),x_u_s_str(i,1:nn_us)-
axial_spc(i),'b')

%
%##pressure surface

tb_l_str(i)=-tb_str(i);
r_0_l_str(i)=-r_0_str(i);
dd_l_str(i)=y_orig_str(i)+tb_l_str(i)/2-r_0_l_str(i)*sind(theta_str(i)/2);
Rlo_str(i)=(dd_l_str(i)^2-r_0_l_str(i)^2+(chord_str(i)/2-
r_0_l_str(i)*cosd(theta_str(i)/2))^2)/(2*(dd_l_str(i)-r_0_l_str(i)));
theta_lo_str(i)=2*asind(chord_str(i)/2-
r_0_l_str(i)*cosd(theta_str(i)/2))*(1/(Rlo_str(i)-r_0_l_str(i)));
```

```
x_l_str_int1(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_l_str_int2(i)=(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));


if i==1

    x_l_str1=[(x_l_str_int1(i):0.001:x_l_str_int2(i))];
    nn1_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));

else

    nn_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));

x_l_str1=[x_l_str1;[(x_l_str_int1(i):0.001:x_l_str_int2(i)),zeros(1,nn1_ls-
nn_ls)]];

end




clear x_l_str
if i==1
    nn_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));
end
    x_l_str=x_l_str1(i,1:nn_ls);

y_l_orig_str(i,1:nn_ls)=y_orig_str(i)+tb_l_str(i)/2-Rlo_str(i);
% behaviour of pressure surface in y direction
y_l_str(i,1:nn_ls)=y_l_orig_str(i,1:nn_ls)+sqrt(Rlo_str(i)^2-x_l_str.^2);
%staggered blade
x_l_s_str(i,1:nn_ls)=x_l_str*cosd(stagger_str(i))-
y_l_str(i,1:nn_ls)*sind(stagger_str(i));
y_l_s_str(i,1:nn_ls)=x_l_str*sind(stagger_str(i))+y_l_str(i,1:nn_ls)*cosd(s
tagger_str(i));


% pressure surface plot
plot(y_l_s_str(i,1:nn_ls),x_l_s_str(i,1:nn_ls)-axial_spc(i),'b')
plot(y_l_s_str(i,1:nn_ls)+spacing_str(i),x_l_s_str(i,1:nn_ls)-
axial_spc(i),'b')
plot(y_l_s_str(i,1:nn_ls)-spacing_str(i),x_l_s_str(i,1:nn_ls)-
axial_spc(i),'b')

%nose design
y_n_str(i)=r_0_str(i)*sind(theta_str(i)/2);
x_n1_str(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_n2_str(i)=chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2);
ang1=0:0.001:2*pi;
xp_str=r_0_str(i)*cos(ang1);
yp_str=r_0_str(i)*sin(ang1);

x_n1_s_str(i)=x_n1_str(i)*cosd(stagger_str(i))-
y_n_str(i)*sind(stagger_str(i));
x_n2_s_str(i)=x_n2_str(i)*cosd(stagger_str(i))-
y_n_str(i)*sind(stagger_str(i));
y_n1_s_str(i)=x_n1_str(i)*sind(stagger_str(i))+y_n_str(i)*cosd(stagger_str(
i));
```

```
y_n2_s_str(i)=x_n2_str(i)*sind(stagger_str(i))+y_n_str(i)*cosd(stagger_str(
i));

%nose plot
plot(y_n1_s_str(i)+yp_str,x_n1_s_str(i)+xp_str-axial_spc(i),'b')
plot(y_n2_s_str(i)+yp_str,x_n2_s_str(i)+xp_str-axial_spc(i),'b')
plot(y_n1_s_str(i)+spacing_str(i)+yp_str,x_n1_s_str(i)+xp_str-
axial_spc(i),'b')
plot(y_n1_s_str(i)-spacing_str(i)+yp_str,x_n1_s_str(i)+xp_str-
axial_spc(i),'b')
plot(y_n2_s_str(i)+spacing_str(i)+yp_str,x_n2_s_str(i)+xp_str-
axial_spc(i),'b')
plot(y_n2_s_str(i)-spacing_str(i)+yp_str,x_n2_s_str(i)+xp_str-
axial_spc(i),'b')
xlabel('[m]')
ylabel('[m]')
title(['STAGE NUMBER:',num2str(i),])
 axis equal

hold off
```

B4, Blade shape hub to tip plot

```
%######################################################################
%##                                                                  ##
%##                  Blade shape hub to tip plot                     ##
%##                                                                  ##
%##                     Daniele Perrotti 2013                        ##
%##                                                                  ##
%##              Lund University/Dept of Energy Sciences             ##
%##                                                                  ##
%######################################################################

globalvariables
global  i chord_rtr



%#################### rotor ################################

theta_rtr(i)= STG(i).camber_angle_rtr;
stagger_rtr(i)= STG(i).stagger_angle_rtr;
chord_rtr(i)= STG(i).chord_rtr;
tb_rtr(i)=STG(i).TONC_rtr.*chord_rtr(i);
r_0_rtr(i)=0.1.*tb_rtr(i);


%radius of curvature
R_c_rtr(i)=chord_rtr(i)*1./(2*sind(theta_rtr(i)./2));

%origin of curvature
orig_c_rtr(i)=-R_c_rtr(i)*cosd(theta_rtr(i)./2);

%chord in x

if i==1
```

```
    x_c_rtr1=[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2)];
    nn1=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
else

    nn=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
    x_c_rtr1=[x_c_rtr1;[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2),zeros(1,nn1-
nn)]];
end

clear x_c_rtr
if i==1
    nn=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
end
    x_c_rtr=x_c_rtr1(i,1:nn);



% behaviour of chord in y direction
y_c_rtr(i,1:nn)=orig_c_rtr(i)+sqrt(R_c_rtr(i)^2-x_c_rtr.^2);
%staggered blade
x_c_s_rtr(i,1:nn)=x_c_rtr.*cosd(stagger_rtr(i))+y_c_rtr(i,1:nn).*sind(stagg
er_rtr(i));
y_c_s_rtr(i,1:nn)=x_c_rtr.*sind(stagger_rtr(i))-
y_c_rtr(i,1:nn).*cosd(stagger_rtr(i));

% p =[ 23   152   560   420];
% set(0, 'DefaultFigurePosition', p)



figure(CompInfo.N_stg+1+i)
%chord plot


subplot(1,2,1);plot3(y_c_s_rtr(i,1:nn),x_c_s_rtr(i,1:nn),repmat(STG(i).r_rm
s_rtr,size(y_c_s_rtr(i,1:nn))),'--r')
hold on


%#########    suction surface
%camberline coordinate at origin of the chord

y_orig_rtr(i)=(chord_rtr(i)./2).*tand(theta_rtr(i)./4);




dd_rtr(i)=y_orig_rtr(i)+tb_rtr(i)./2-r_0_rtr(i).*sind(theta_rtr(i)./2);
%radius of curvature
Rup_rtr(i)=(dd_rtr(i).^2-r_0_rtr(i).^2+(chord_rtr(i)./2-
r_0_rtr(i).*cosd(theta_rtr(i)./2)).^2)/(2.*(dd_rtr(i)-r_0_rtr(i)));


x_u_rtr_int1(i)=-(chord_rtr(i)./2-r_0_rtr(i).*cosd(theta_rtr(i)./2));
%interval between the begin and half chord
```

```
x_u_rtr_int2(i)=(chord_rtr(i)./2-r_0_rtr(i).*cosd(theta_rtr(i)./2));
%interval between  half chord and the end

%3d matrix
if i==1

    x_u_rtr1=[(x_u_rtr_int1(i):0.001:x_u_rtr_int2(i))];
    nn1_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));

else

    nn_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));

x_u_rtr1=[x_u_rtr1;[(x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)),zeros(1,nn1_u-
nn_u)]];

end




clear x_u_rtr
if i==1
    nn_u=length((x_u_rtr_int1(i):0.001:x_u_rtr_int2(i)));
end
    x_u_rtr=x_u_rtr1(i,1:nn_u);


y_u_orig_rtr(i,1:nn_u)=y_orig_rtr(i)+tb_rtr(i)/2-Rup_rtr(i);
% behaviour of suction surface in y direction
y_u_rtr(i,1:nn_u)=y_u_orig_rtr(i,1:nn_u)+sqrt(Rup_rtr(i)^2-x_u_rtr.^2);
%staggered blade
x_u_s_rtr(i,1:nn_u)=x_u_rtr*cosd(stagger_rtr(i))+y_u_rtr(i,1:nn_u)*sind(sta
gger_rtr(i));
y_u_s_rtr(i,1:nn_u)=x_u_rtr*sind(stagger_rtr(i))-
y_u_rtr(i,1:nn_u)*cosd(stagger_rtr(i));

% suction surface plot

subplot(1,2,1);plot3(y_u_s_rtr(i,1:nn_u),x_u_s_rtr(i,1:nn_u),repmat(STG(i).
r_rms_rtr,size(y_u_s_rtr(i,1:nn_u))),'r')
 %########pressure surface

tb_l_rtr(i)=-tb_rtr(i);
r_0_l_rtr(i)=-r_0_rtr(i);
dd_l_rtr(i)=y_orig_rtr(i)+tb_l_rtr(i)/2-r_0_l_rtr(i)*sind(theta_rtr(i)/2);
Rlo_rtr(i)=(dd_l_rtr(i)^2-r_0_l_rtr(i)^2+(chord_rtr(i)/2-
r_0_l_rtr(i)*cosd(theta_rtr(i)/2))^2)/(2*(dd_l_rtr(i)-r_0_l_rtr(i)));

x_l_rtr_int1(i)=-(chord_rtr(i)/2-r_0_l_rtr(i)*cosd(theta_rtr(i)/2));
x_l_rtr_int2(i)=(chord_rtr(i)/2-r_0_l_rtr(i)*cosd(theta_rtr(i)/2));

if i==1

    x_l_rtr1=[(x_l_rtr_int1(i):0.001:x_l_rtr_int2(i))];
    nn1_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));

else
```

```
    nn_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));

x_l_rtr1=[x_l_rtr1;[(x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)),zeros(1,nn1_l-
nn_l)]];

end




clear x_l_rtr
if i==1
    nn_l=length((x_l_rtr_int1(i):0.001:x_l_rtr_int2(i)));
end
    x_l_rtr=x_l_rtr1(i,1:nn_l);

y_l_orig_rtr(i,1:nn_l)=y_orig_rtr(i)+tb_l_rtr(i)/2-Rlo_rtr(i);
% behaviour of pressure surface in y direction
y_l_rtr(i,1:nn_l)=y_l_orig_rtr(i,1:nn_l)+sqrt(Rlo_rtr(i)^2-x_l_rtr.^2);
%staggered blade
x_l_s_rtr(i,1:nn_l)=x_l_rtr*cosd(stagger_rtr(i))+y_l_rtr(i,1:nn_l)*sind(sta
gger_rtr(i));
y_l_s_rtr(i,1:nn_l)=x_l_rtr*sind(stagger_rtr(i))-
y_l_rtr(i,1:nn_l)*cosd(stagger_rtr(i));




% pressure surface plot

subplot(1,2,1);plot3(y_l_s_rtr(i,1:nn_l),x_l_s_rtr(i,1:nn_l),repmat(STG(i).
r_rms_rtr,size(y_l_s_rtr(i,1:nn_l))),'r');

%nose design
y_n_rtr(i)=r_0_rtr(i)*sind(theta_rtr(i)/2);
x_n1_rtr(i)=-(chord_rtr(i)/2-r_0_rtr(i)*cosd(theta_rtr(i)/2));
x_n2_rtr(i)=chord_rtr(i)/2-r_0_rtr(i)*cosd(theta_rtr(i)/2);
ang1=0:0.001:2*pi;
xp_rtr=r_0_rtr(i).*cos(ang1);
yp_rtr=r_0_rtr(i).*sin(ang1);

x_n1_s_rtr(i)=x_n1_rtr(i)*cosd(stagger_rtr(i))+y_n_rtr(i)*sind(stagger_rtr(
i));
x_n2_s_rtr(i)=x_n2_rtr(i)*cosd(stagger_rtr(i))+y_n_rtr(i)*sind(stagger_rtr(
i));
y_n1_s_rtr(i)=x_n1_rtr(i)*sind(stagger_rtr(i))-
y_n_rtr(i)*cosd(stagger_rtr(i));
y_n2_s_rtr(i)=x_n2_rtr(i)*sind(stagger_rtr(i))-
y_n_rtr(i)*cosd(stagger_rtr(i));

%nose plot

subplot(1,2,1);plot3(y_n1_s_rtr(i)+yp_rtr,x_n1_s_rtr(i)+xp_rtr,repmat(STG(i
).r_rms_rtr,size(y_n1_s_rtr(i)+yp_rtr)),'r');
subplot(1,2,1);plot3(y_n2_s_rtr(i)+yp_rtr,x_n2_s_rtr(i)+xp_rtr,repmat(STG(i
).r_rms_rtr,size(y_n2_s_rtr(i)+yp_rtr)),'r');
```

```
%#################HUB#############################################

if proj_law == 'FoV'
    theta_rtr_hub(i)= STG(i).camber_angle_rtr_FV_hub;
    stagger_rtr_hub(i)= STG(i).stagger_angle_rtr_FV_hub;
    tb_rtr_hub(i)=STG(i).TONC_rtr_hub.*chord_rtr(i);
    r_0_rtr_hub(i)=0.1.*tb_rtr_hub(i);

elseif proj_law == 'MFV'
    theta_rtr_hub(i)= STG(i).camber_angle_rtr_FREEV_hub;
    stagger_rtr_hub(i)= STG(i).stagger_angle_rtr_FREEV_hub;
    tb_rtr_hub(i)=STG(i).TONC_rtr_hub.*chord_rtr(i);
    r_0_rtr_hub(i)=0.1.*tb_rtr_hub(i);
end




%#################### rotor ################################


%radius of curvature
R_c_rtr_hub(i)=chord_rtr(i)*1./(2*sind(theta_rtr_hub(i)./2));

%origin of curvature
orig_c_rtr_hub(i)=-R_c_rtr_hub(i)*cosd(theta_rtr_hub(i)./2);


if i==1

    x_c_rtr1_hub=[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2)];
    nn1_hub=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
else

    nn_hub=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
    x_c_rtr1_hub=[x_c_rtr1_hub;[(-
chord_rtr(i)/2:0.001:chord_rtr(i)/2),zeros(1,nn1_hub-nn_hub)]];
end

clear x_c_rtr
if i==1
    nn_hub=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
end
    x_c_rtr_hub=x_c_rtr1_hub(i,1:nn_hub);



% behaviour of chord in y direction
y_c_rtr_hub(i,1:nn_hub)=orig_c_rtr_hub(i)+sqrt(R_c_rtr_hub(i)^2-
x_c_rtr_hub.^2);
%staggered blade
x_c_s_rtr_hub(i,1:nn_hub)=x_c_rtr_hub.*cosd(stagger_rtr_hub(i))+y_c_rtr_hub
(i,1:nn_hub).*sind(stagger_rtr_hub(i));
y_c_s_rtr_hub(i,1:nn_hub)=x_c_rtr_hub.*sind(stagger_rtr_hub(i))-
y_c_rtr_hub(i,1:nn_hub).*cosd(stagger_rtr_hub(i));
```

```
%chord plot

subplot(1,2,1);plot3(y_c_s_rtr_hub(i,1:nn_hub),x_c_s_rtr_hub(i,1:nn_hub),re
pmat(STG(i).r_hub_rtr,size(y_c_s_rtr_hub(i,1:nn_hub))),'--','Color',[1
99/255 71/255])


%  axis([-0.1 0.1 -0.1 0.1])

%#########    suction surface
%camberline coordinate at origin of the chord

y_orig_rtr_hub(i)=(chord_rtr(i)./2).*tand(theta_rtr_hub(i)./4);




dd_rtr_hub(i)=y_orig_rtr_hub(i)+tb_rtr_hub(i)./2-
r_0_rtr_hub(i).*sind(theta_rtr_hub(i)./2);
%radius of curvature
Rup_rtr_hub(i)=(dd_rtr_hub(i).^2-r_0_rtr_hub(i).^2+(chord_rtr(i)./2-
r_0_rtr_hub(i).*cosd(theta_rtr_hub(i)./2)).^2)/(2.*(dd_rtr_hub(i)-
r_0_rtr_hub(i)));


x_u_rtr_int1_hub(i)=-(chord_rtr(i)./2-
r_0_rtr_hub(i).*cosd(theta_rtr_hub(i)./2));
x_u_rtr_int2_hub(i)=(chord_rtr(i)./2-
r_0_rtr_hub(i).*cosd(theta_rtr_hub(i)./2));

if i==1

    x_u_rtr1_hub=[(x_u_rtr_int1_hub(i):0.001:x_u_rtr_int2_hub(i))];
    nn1_u_hub=length((x_u_rtr_int1_hub(i):0.001:x_u_rtr_int2_hub(i)));

else

    nn_u_hub=length((x_u_rtr_int1_hub(i):0.001:x_u_rtr_int2_hub(i)));

x_u_rtr1_hub=[x_u_rtr1_hub;[(x_u_rtr_int1_hub(i):0.001:x_u_rtr_int2_hub(i))
,zeros(1,nn1_u_hub-nn_u_hub)]];

end




clear x_u_rtr_hub
if i==1
    nn_u_hub=length((x_u_rtr_int1_hub(i):0.001:x_u_rtr_int2_hub(i)));
end
    x_u_rtr_hub=x_u_rtr1_hub(i,1:nn_u_hub);


y_u_orig_rtr_hub(i,1:nn_u_hub)=y_orig_rtr_hub(i)+tb_rtr_hub(i)/2-
Rup_rtr_hub(i);
```

```
3% behaviour of suction surface in y direction
y_u_rtr_hub(i,1:nn_u_hub)=y_u_orig_rtr_hub(i,1:nn_u_hub)+sqrt(Rup_rtr_hub(i
)^2-x_u_rtr_hub.^2);
%staggered blade
x_u_s_rtr_hub(i,1:nn_u_hub)=x_u_rtr_hub*cosd(stagger_rtr_hub(i))+y_u_rtr_hu
b(i,1:nn_u_hub)*sind(stagger_rtr_hub(i));
y_u_s_rtr_hub(i,1:nn_u_hub)=x_u_rtr_hub*sind(stagger_rtr_hub(i))-
y_u_rtr_hub(i,1:nn_u_hub)*cosd(stagger_rtr_hub(i));

% suction surface plot

subplot(1,2,1);plot3(y_u_s_rtr_hub(i,1:nn_u_hub),x_u_s_rtr_hub(i,1:nn_u_hub
),repmat(STG(i).r_hub_rtr,size(y_u_s_rtr_hub(i,1:nn_u_hub))),'Color',[1
99/255 71/255]);

 %########pressure surface

tb_l_rtr_hub(i)=-tb_rtr_hub(i);
r_0_l_rtr_hub(i)=-r_0_rtr_hub(i);
dd_l_rtr_hub(i)=y_orig_rtr_hub(i)+tb_l_rtr_hub(i)/2-
r_0_l_rtr_hub(i)*sind(theta_rtr_hub(i)/2);
Rlo_rtr_hub(i)=(dd_l_rtr_hub(i)^2-r_0_l_rtr_hub(i)^2+(chord_rtr(i)/2-
r_0_l_rtr_hub(i)*cosd(theta_rtr_hub(i)/2))^2)/(2*(dd_l_rtr_hub(i)-
r_0_l_rtr_hub(i)));

x_l_rtr_int1_hub(i)=-(chord_rtr(i)/2-
r_0_l_rtr_hub(i)*cosd(theta_rtr_hub(i)/2));
x_l_rtr_int2_hub(i)=(chord_rtr(i)/2-
r_0_l_rtr_hub(i)*cosd(theta_rtr_hub(i)/2));

if i==1

    x_l_rtr1_hub=[(x_l_rtr_int1_hub(i):0.001:x_l_rtr_int2_hub(i))];
    nn1_l_hub=length((x_l_rtr_int1_hub(i):0.001:x_l_rtr_int2_hub(i)));

else

    nn_l_hub=length((x_l_rtr_int1_hub(i):0.001:x_l_rtr_int2_hub(i)));

x_l_rtr1_hub=[x_l_rtr1_hub;[(x_l_rtr_int1_hub(i):0.001:x_l_rtr_int2_hub(i))
,zeros(1,nn1_l_hub-nn_l_hub)]];

end

clear x_l_rtr_hub
if i==1
    nn_l_hub=length((x_l_rtr_int1_hub(i):0.001:x_l_rtr_int2_hub(i)));
end
    x_l_rtr_hub=x_l_rtr1_hub(i,1:nn_l_hub);

y_l_orig_rtr_hub(i,1:nn_l_hub)=y_orig_rtr_hub(i)+tb_l_rtr_hub(i)/2-
Rlo_rtr_hub(i);
% behaviour of pressure surface in y direction
y_l_rtr_hub(i,1:nn_l_hub)=y_l_orig_rtr_hub(i,1:nn_l_hub)+sqrt(Rlo_rtr_hub(i
)^2-x_l_rtr_hub.^2);
%staggered blade
x_l_s_rtr_hub(i,1:nn_l_hub)=x_l_rtr_hub*cosd(stagger_rtr_hub(i))+y_l_rtr_hu
b(i,1:nn_l_hub)*sind(stagger_rtr_hub(i));
```

```
y_l_s_rtr_hub(i,1:nn_l_hub)=x_l_rtr_hub*sind(stagger_rtr_hub(i))-
y_l_rtr_hub(i,1:nn_l_hub)*cosd(stagger_rtr_hub(i));




% pressure surface plot

subplot(1,2,1);plot3(y_l_s_rtr_hub(i,1:nn_l_hub),x_l_s_rtr_hub(i,1:nn_l_hub
),repmat(STG(i).r_hub_rtr,size(y_l_s_rtr_hub(i,1:nn_l_hub))),'Color',[1
99/255 71/255]);



%nose design
y_n_rtr_hub(i)=r_0_rtr_hub(i)*sind(theta_rtr_hub(i)/2);
x_n1_rtr_hub(i)=-(chord_rtr(i)/2-r_0_rtr_hub(i)*cosd(theta_rtr_hub(i)/2));
x_n2_rtr_hub(i)=chord_rtr(i)/2-r_0_rtr_hub(i)*cosd(theta_rtr_hub(i)/2);
ang1=0:0.001:2*pi;
xp_rtr_hub=r_0_rtr_hub(i).*cos(ang1);
yp_rtr_hub=r_0_rtr_hub(i).*sin(ang1);

x_n1_s_rtr_hub(i)=x_n1_rtr_hub(i)*cosd(stagger_rtr_hub(i))+y_n_rtr_hub(i)*s
ind(stagger_rtr_hub(i));
x_n2_s_rtr_hub(i)=x_n2_rtr_hub(i)*cosd(stagger_rtr_hub(i))+y_n_rtr_hub(i)*s
ind(stagger_rtr_hub(i));
y_n1_s_rtr_hub(i)=x_n1_rtr_hub(i)*sind(stagger_rtr_hub(i))-
y_n_rtr_hub(i)*cosd(stagger_rtr_hub(i));
y_n2_s_rtr_hub(i)=x_n2_rtr_hub(i)*sind(stagger_rtr_hub(i))-
y_n_rtr_hub(i)*cosd(stagger_rtr_hub(i));

%nose plot

subplot(1,2,1);plot3(y_n1_s_rtr_hub(i)+yp_rtr_hub,x_n1_s_rtr_hub(i)+xp_rtr_
hub,repmat(STG(i).r_hub_rtr,size(y_n1_s_rtr_hub(i)+yp_rtr_hub)),'Color',[1
99/255 71/255]);
subplot(1,2,1);plot3(y_n2_s_rtr_hub(i)+yp_rtr_hub,x_n2_s_rtr_hub(i)+xp_rtr_
hub,repmat(STG(i).r_hub_rtr,size(y_n2_s_rtr_hub(i)+yp_rtr_hub)),'Color',[1
99/255 71/255]);

% ################## TIP ###########################################

if proj_law == 'FoV'
    theta_rtr_tip(i)= STG(i).camber_angle_rtr_FV_tip;
    stagger_rtr_tip(i)= STG(i).stagger_angle_rtr_FV_tip;
    tb_rtr_tip(i)=STG(i).TONC_rtr_tip.*chord_rtr(i);
    r_0_rtr_tip(i)=0.1.*tb_rtr_tip(i);

elseif proj_law == 'MFV'
    theta_rtr_tip(i)= STG(i).camber_angle_rtr_FREEV_tip;
    stagger_rtr_tip(i)= STG(i).stagger_angle_rtr_FREEV_tip;
    tb_rtr_tip(i)=STG(i).TONC_rtr_tip.*chord_rtr(i);
    r_0_rtr_tip(i)=0.1.*tb_rtr_tip(i);
end




% #################### rotor ################################
```

```
% radius of curvature
R_c_rtr_tip(i)=chord_rtr(i)*1./(2*sind(theta_rtr_tip(i)./2));

% origin of curvature
orig_c_rtr_tip(i)=-R_c_rtr_tip(i)*cosd(theta_rtr_tip(i)./2);


if i==1

    x_c_rtr1_tip=[(-chord_rtr(i)/2:0.001:chord_rtr(i)/2)];
    nn1_tip=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
else

    nn_tip=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
    x_c_rtr1_tip=[x_c_rtr1_tip;[(-
chord_rtr(i)/2:0.001:chord_rtr(i)/2),zeros(1,nn1_tip-nn_tip)]];
end

clear x_c_rtr
if i==1
    nn_tip=length((-chord_rtr(i)/2:0.001:chord_rtr(i)/2));
end
    x_c_rtr_tip=x_c_rtr1_tip(i,1:nn_tip);



% behaviour of chord in y direction
y_c_rtr_tip(i,1:nn_tip)=orig_c_rtr_tip(i)+sqrt(R_c_rtr_tip(i)^2-
x_c_rtr_tip.^2);
% staggered blade
x_c_s_rtr_tip(i,1:nn_tip)=x_c_rtr_tip.*cosd(stagger_rtr_tip(i))+y_c_rtr_tip
(i,1:nn_tip).*sind(stagger_rtr_tip(i));
y_c_s_rtr_tip(i,1:nn_tip)=x_c_rtr_tip.*sind(stagger_rtr_tip(i))-
y_c_rtr_tip(i,1:nn_tip).*cosd(stagger_rtr_tip(i));


% chord plot

subplot(1,2,1);plot3(y_c_s_rtr_tip(i,1:nn_tip),x_c_s_rtr_tip(i,1:nn_tip),re
pmat(STG(i).r_tip_rtr,size(y_c_s_rtr_tip(i,1:nn_tip))),'--
','Color',[139/255 0 0])



% #########    suction surface
% camberline coordinate at origin of the chord

y_orig_rtr_tip(i)=(chord_rtr(i)./2).*tand(theta_rtr_tip(i)./4);



dd_rtr_tip(i)=y_orig_rtr_tip(i)+tb_rtr_tip(i)./2-
r_0_rtr_tip(i).*sind(theta_rtr_tip(i)./2);
% radius of curvature
```

```
Rup_rtr_tip(i)=(dd_rtr_tip(i).^2-r_0_rtr_tip(i).^2+(chord_rtr(i)./2-
r_0_rtr_tip(i).*cosd(theta_rtr_tip(i)./2)).^2)/(2.*(dd_rtr_tip(i)-
r_0_rtr_tip(i)));


x_u_rtr_int1_tip(i)=-(chord_rtr(i)./2-
r_0_rtr_tip(i).*cosd(theta_rtr_tip(i)./2));
x_u_rtr_int2_tip(i)=(chord_rtr(i)./2-
r_0_rtr_tip(i).*cosd(theta_rtr_tip(i)./2));

if i==1

    x_u_rtr1_tip=[(x_u_rtr_int1_tip(i):0.001:x_u_rtr_int2_tip(i))];
    nn1_u_tip=length((x_u_rtr_int1_tip(i):0.001:x_u_rtr_int2_tip(i)));

else

    nn_u_tip=length((x_u_rtr_int1_tip(i):0.001:x_u_rtr_int2_tip(i)));

x_u_rtr1_tip=[x_u_rtr1_tip;[(x_u_rtr_int1_tip(i):0.001:x_u_rtr_int2_tip(i))
,zeros(1,nn1_u_tip-nn_u_tip)]];

end




clear x_u_rtr_tip
if i==1
    nn_u_tip=length((x_u_rtr_int1_tip(i):0.001:x_u_rtr_int2_tip(i)));
end
    x_u_rtr_tip=x_u_rtr1_tip(i,1:nn_u_tip);


y_u_orig_rtr_tip(i,1:nn_u_tip)=y_orig_rtr_tip(i)+tb_rtr_tip(i)/2-
Rup_rtr_tip(i);
% behaviour of suction surface in y direction
y_u_rtr_tip(i,1:nn_u_tip)=y_u_orig_rtr_tip(i,1:nn_u_tip)+sqrt(Rup_rtr_tip(i
)^2-x_u_rtr_tip.^2);
% staggered blade
x_u_s_rtr_tip(i,1:nn_u_tip)=x_u_rtr_tip*cosd(stagger_rtr_tip(i))+y_u_rtr_ti
p(i,1:nn_u_tip)*sind(stagger_rtr_tip(i));
y_u_s_rtr_tip(i,1:nn_u_tip)=x_u_rtr_tip*sind(stagger_rtr_tip(i))-
y_u_rtr_tip(i,1:nn_u_tip)*cosd(stagger_rtr_tip(i));

% suction surface plot

subplot(1,2,1);plot3(y_u_s_rtr_tip(i,1:nn_u_tip),x_u_s_rtr_tip(i,1:nn_u_tip
),repmat(STG(i).r_tip_rtr,size(y_u_s_rtr_tip(i,1:nn_u_tip))),'Color',[139/2
55 0 0])

%  ########pressure surface

tb_l_rtr_tip(i)=-tb_rtr_tip(i);
r_0_l_rtr_tip(i)=-r_0_rtr_tip(i);
dd_l_rtr_tip(i)=y_orig_rtr_tip(i)+tb_l_rtr_tip(i)/2-
r_0_l_rtr_tip(i)*sind(theta_rtr_tip(i)/2);
```

```
Rlo_rtr_tip(i)=(dd_l_rtr_tip(i)^2-r_0_l_rtr_tip(i)^2+(chord_rtr(i)/2-
r_0_l_rtr_tip(i)*cosd(theta_rtr_tip(i)/2))^2)/(2*(dd_l_rtr_tip(i)-
r_0_l_rtr_tip(i)));

x_l_rtr_int1_tip(i)=-(chord_rtr(i)/2-
r_0_l_rtr_tip(i)*cosd(theta_rtr_tip(i)/2));
x_l_rtr_int2_tip(i)=(chord_rtr(i)/2-
r_0_l_rtr_tip(i)*cosd(theta_rtr_tip(i)/2));

if i==1

    x_l_rtr1_tip=[(x_l_rtr_int1_tip(i):0.001:x_l_rtr_int2_tip(i))];
    nn1_l_tip=length((x_l_rtr_int1_tip(i):0.001:x_l_rtr_int2_tip(i)));

else

    nn_l_tip=length((x_l_rtr_int1_tip(i):0.001:x_l_rtr_int2_tip(i)));

x_l_rtr1_tip=[x_l_rtr1_tip;[(x_l_rtr_int1_tip(i):0.001:x_l_rtr_int2_tip(i))
,zeros(1,nn1_l_tip-nn_l_tip)]];

end




clear x_l_rtr_tip
if i==1
    nn_l_tip=length((x_l_rtr_int1_tip(i):0.001:x_l_rtr_int2_tip(i)));
end
    x_l_rtr_tip=x_l_rtr1_tip(i,1:nn_l_tip);

y_l_orig_rtr_tip(i,1:nn_l_tip)=y_orig_rtr_tip(i)+tb_l_rtr_tip(i)/2-
Rlo_rtr_tip(i);
% behaviour of pressure surface in y direction
y_l_rtr_tip(i,1:nn_l_tip)=y_l_orig_rtr_tip(i,1:nn_l_tip)+sqrt(Rlo_rtr_tip(i
)^2-x_l_rtr_tip.^2);
% staggered blade
x_l_s_rtr_tip(i,1:nn_l_tip)=x_l_rtr_tip*cosd(stagger_rtr_tip(i))+y_l_rtr_ti
p(i,1:nn_l_tip)*sind(stagger_rtr_tip(i));
y_l_s_rtr_tip(i,1:nn_l_tip)=x_l_rtr_tip*sind(stagger_rtr_tip(i))-
y_l_rtr_tip(i,1:nn_l_tip)*cosd(stagger_rtr_tip(i));




% pressure surface plot

subplot(1,2,1);plot3(y_l_s_rtr_tip(i,1:nn_l_tip),x_l_s_rtr_tip(i,1:nn_l_tip
),repmat(STG(i).r_tip_rtr,size(y_l_s_rtr_tip(i,1:nn_l_tip))),'Color',[139/2
55 0 0]);

% nose design
y_n_rtr_tip(i)=r_0_rtr_tip(i)*sind(theta_rtr_tip(i)/2);
x_n1_rtr_tip(i)=-(chord_rtr(i)/2-r_0_rtr_tip(i)*cosd(theta_rtr_tip(i)/2));
x_n2_rtr_tip(i)=chord_rtr(i)/2-r_0_rtr_tip(i)*cosd(theta_rtr_tip(i)/2);
ang1=0:0.001:2*pi;
xp_rtr_tip=r_0_rtr_tip(i).*cos(ang1);
```

```
yp_rtr_tip=r_0_rtr_tip(i).*sin(ang1);

x_n1_s_rtr_tip(i)=x_n1_rtr_tip(i)*cosd(stagger_rtr_tip(i))+y_n_rtr_tip(i)*s
ind(stagger_rtr_tip(i));
x_n2_s_rtr_tip(i)=x_n2_rtr_tip(i)*cosd(stagger_rtr_tip(i))+y_n_rtr_tip(i)*s
ind(stagger_rtr_tip(i));
y_n1_s_rtr_tip(i)=x_n1_rtr_tip(i)*sind(stagger_rtr_tip(i))-
y_n_rtr_tip(i)*cosd(stagger_rtr_tip(i));
y_n2_s_rtr_tip(i)=x_n2_rtr_tip(i)*sind(stagger_rtr_tip(i))-
y_n_rtr_tip(i)*cosd(stagger_rtr_tip(i));

% nose plot

subplot(1,2,1);plot3(y_n1_s_rtr_tip(i)+yp_rtr_tip,x_n1_s_rtr_tip(i)+xp_rtr_
tip,repmat(STG(i).r_tip_rtr,size(y_n1_s_rtr_tip(i)+yp_rtr_tip)),'Color',[13
9/255 0 0]);
subplot(1,2,1);plot3(y_n2_s_rtr_tip(i)+yp_rtr_tip,x_n2_s_rtr_tip(i)+xp_rtr_
tip,repmat(STG(i).r_tip_rtr,size(y_n2_s_rtr_tip(i)+yp_rtr_tip)),'Color',[13
9/255 0 0]);
title(['Rotor Shape for Stage Number:',num2str(i),])
xlabel('[m]')
ylabel('[m]')
zlabel('[m]')
axis equal
grid on
hold off

%################stator########################

theta_str(i)=STG(i).camber_angle_str;
chord_str(i)=STG(i).chord_str;
stagger_str(i)=-STG(i).stagger_angle_str;
tb_str(i)=STG(i).TONC_str.*chord_str(i);
r_0_str(i)=0.1.*tb_str(i);



%radius of curvature
R_c_str(i)=chord_str(i)*1./(2*sind(theta_str(i)./2));

%origin of curvature
orig_c_str(i)=-R_c_str(i)*cosd(theta_str(i)./2);

%chord in x



if i==1

    x_c_str1=[(-chord_str(i)/2:0.001:chord_str(i)/2)];
    nn1s=length((-chord_str(i)/2:0.001:chord_str(i)/2));
else

    nns=length((-chord_str(i)/2:0.001:chord_str(i)/2));
    x_c_str1=[x_c_str1;[(-
chord_str(i)/2:0.001:chord_str(i)/2),zeros(1,nn1s-nns)]];
end

clear x_c_str
if i==1
    nns=length((-chord_str(i)/2:0.001:chord_str(i)/2));
```

```
end
    x_c_str=x_c_str1(i,1:nns);

% behaviour of chord in y direction
y_c_str(i,1:nns)=orig_c_str(i)+sqrt(R_c_str(i)^2-x_c_str.^2);
%staggered blade
x_c_s_str(i,1:nns)=x_c_str.*cosd(stagger_str(i))-
y_c_str(i,1:nns).*sind(stagger_str(i));% sign of y changed
y_c_s_str(i,1:nns)=x_c_str.*sind(stagger_str(i))+y_c_str(i,1:nns).*cosd(sta
gger_str(i));


%chord plot

subplot(1,2,2); plot3(y_c_s_str(i,1:nns),-
x_c_s_str(i,1:nns),repmat(STG(i).r_rms_str,size(y_c_s_str(i,1:nns))),'--b')
% - for the x to plot the blade in the right way
hold on
%####suction surface

%camberline coordinate at origin of the chord
y_orig_str(i)=(chord_str(i)/2)*tand(theta_str(i)/4);

dd_str(i)=y_orig_str(i)+tb_str(i)/2-r_0_str(i)*sind(theta_str(i)/2);
Rup_str(i)=(dd_str(i)^2-r_0_str(i)^2+(chord_str(i)/2-
r_0_str(i)*cosd(theta_str(i)/2))^2)/(2*(dd_str(i)-r_0_str(i)));
theta_up_str(i)=2*asind(chord_str(i)/2-
r_0_str(i)*cosd(theta_str(i)/2))*(1/(Rup_str(i)-r_0_str(i)));

x_u_str_int1(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_u_str_int2(i)=(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));

if i==1

    x_u_str1=[(x_u_str_int1(i):0.001:x_u_str_int2(i))];
    nn1_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));

else

    nn_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));

x_u_str1=[x_u_str1;[(x_u_str_int1(i):0.001:x_u_str_int2(i)),zeros(1,nn1_us-
nn_us)]];

end

clear x_u_str
if i==1
    nn_us=length((x_u_str_int1(i):0.001:x_u_str_int2(i)));
end
    x_u_str=x_u_str1(i,1:nn_us);


y_u_orig_str(i,1:nn_us)=y_orig_str(i)+tb_str(i)/2-Rup_str(i);

y_u_str(i,1:nn_us)=y_u_orig_str(i)+sqrt(Rup_str(i)^2-x_u_str.^2);
x_u_s_str(i,1:nn_us)=x_u_str*cosd(stagger_str(i))-
y_u_str(i,1:nn_us)*sind(stagger_str(i));
```

```
y_u_s_str(i,1:nn_us)=x_u_str*sind(stagger_str(i))+y_u_str(i,1:nn_us)*cosd(s
tagger_str(i));


% suction surface plot
 subplot(1,2,2);plot3(y_u_s_str(i,1:nn_us),-
x_u_s_str(i,1:nn_us),repmat(STG(i).r_rms_str,size(y_u_s_str(i,1:nn_us))),'b
')

%##pressure surface

tb_l_str(i)=-tb_str(i);
r_0_l_str(i)=-r_0_str(i);
dd_l_str(i)=y_orig_str(i)+tb_l_str(i)/2-r_0_l_str(i)*sind(theta_str(i)/2);
Rlo_str(i)=(dd_l_str(i)^2-r_0_l_str(i)^2+(chord_str(i)/2-
r_0_l_str(i)*cosd(theta_str(i)/2))^2)/(2*(dd_l_str(i)-r_0_l_str(i)));
theta_lo_str(i)=2*asind(chord_str(i)/2-
r_0_l_str(i)*cosd(theta_str(i)/2))*(1/(Rlo_str(i)-r_0_l_str(i)));

x_l_str_int1(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_l_str_int2(i)=(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));


if i==1

    x_l_str1=[(x_l_str_int1(i):0.001:x_l_str_int2(i))];
    nn1_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));

else

    nn_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));

x_l_str1=[x_l_str1;[(x_l_str_int1(i):0.001:x_l_str_int2(i)),zeros(1,nn1_ls-
nn_ls)]];

end




clear x_l_str
if i==1
    nn_ls=length((x_l_str_int1(i):0.001:x_l_str_int2(i)));
end
    x_l_str=x_l_str1(i,1:nn_ls);

y_l_orig_str(i,1:nn_ls)=y_orig_str(i)+tb_l_str(i)/2-Rlo_str(i);
% behaviour of pressure surface in y direction
y_l_str(i,1:nn_ls)=y_l_orig_str(i,1:nn_ls)+sqrt(Rlo_str(i)^2-x_l_str.^2);
%staggered blade
x_l_s_str(i,1:nn_ls)=x_l_str*cosd(stagger_str(i))-
y_l_str(i,1:nn_ls)*sind(stagger_str(i));
y_l_s_str(i,1:nn_ls)=x_l_str*sind(stagger_str(i))+y_l_str(i,1:nn_ls)*cosd(s
tagger_str(i));


% pressure surface plot
```

```
subplot(1,2,2); plot3(y_l_s_str(i,1:nn_ls),-
x_l_s_str(i,1:nn_ls),repmat(STG(i).r_rms_str,size(y_l_s_str(i,1:nn_ls))),'b
')
%nose design
y_n_str(i)=r_0_str(i)*sind(theta_str(i)/2);
x_n1_str(i)=-(chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2));
x_n2_str(i)=chord_str(i)/2-r_0_str(i)*cosd(theta_str(i)/2);
ang1=0:0.001:2*pi;
xp_str=r_0_str(i)*cos(ang1);
yp_str=r_0_str(i)*sin(ang1);

x_n1_s_str(i)=x_n1_str(i)*cosd(stagger_str(i))-
y_n_str(i)*sind(stagger_str(i));
x_n2_s_str(i)=x_n2_str(i)*cosd(stagger_str(i))-
y_n_str(i)*sind(stagger_str(i));
y_n1_s_str(i)=x_n1_str(i)*sind(stagger_str(i))+y_n_str(i)*cosd(stagger_str(
i));
y_n2_s_str(i)=x_n2_str(i)*sind(stagger_str(i))+y_n_str(i)*cosd(stagger_str(
i));

%nose plot

subplot(1,2,2);plot3(y_n1_s_str(i)+yp_str,-
x_n1_s_str(i)+xp_str,repmat(STG(i).r_rms_str,size(y_n1_s_str(i)+yp_str)),'b
');
subplot(1,2,2);plot3(y_n2_s_str(i)+yp_str,-
x_n2_s_str(i)+xp_str,repmat(STG(i).r_rms_str,size(y_n2_s_str(i)+yp_str)),'b
');


% ##### HUB

if proj_law == 'FoV'
    theta_str_hub(i)= STG(i).camber_angle_str_FV_hub;
    stagger_str_hub(i)=- STG(i).stagger_angle_str_FV_hub;
    tb_str_hub(i)=STG(i).TONC_str.*chord_str(i);
    r_0_str_hub(i)=0.1.*tb_str_hub(i);

elseif proj_law == 'MFV'
    theta_str_hub(i)= STG(i).camber_angle_str_FREEV_hub;
    stagger_str_hub(i)= -STG(i).stagger_angle_str_FREEV_hub;
    tb_str_hub(i)=STG(i).TONC_str.*chord_str(i);
    r_0_str_hub(i)=0.1.*tb_str_hub(i);
end

%radius of curvature
R_c_str_hub(i)=chord_str(i)*1./(2*sind(theta_str_hub(i)./2));

%origin of curvature
orig_c_str_hub(i)=-R_c_str_hub(i)*cosd(theta_str_hub(i)./2);

%chord in x


if i==1

    x_c_str1_hub=[(-chord_str(i)/2:0.001:chord_str(i)/2)];
    nn1s_hub=length((-chord_str(i)/2:0.001:chord_str(i)/2));
```

```
else

    nns_hub=length((-chord_str(i)/2:0.001:chord_str(i)/2));
    x_c_str1_hub=[x_c_str1_hub;[(-
chord_str(i)/2:0.001:chord_str(i)/2),zeros(1,nn1s_hub-nns_hub)]];
end

clear x_c_str_hub
if i==1
    nns_hub=length((-chord_str(i)/2:0.001:chord_str(i)/2));
end
    x_c_str_hub=x_c_str1_hub(i,1:nns_hub);

% behaviour of chord in y direction
y_c_str_hub(i,1:nns_hub)=orig_c_str_hub(i)+sqrt(R_c_str_hub(i)^2-
x_c_str_hub.^2);
%staggered blade
x_c_s_str_hub(i,1:nns_hub)=x_c_str_hub.*cosd(stagger_str_hub(i))-
y_c_str_hub(i,1:nns_hub).*sind(stagger_str_hub(i));% sign of y changed
y_c_s_str_hub(i,1:nns_hub)=x_c_str_hub.*sind(stagger_str_hub(i))+y_c_str_hu
b(i,1:nns_hub).*cosd(stagger_str_hub(i));

%chord plot

subplot(1,2,2);plot3(y_c_s_str_hub(i,1:nns_hub),-
x_c_s_str_hub(i,1:nns_hub),repmat(STG(i).r_hub_str,size(y_c_s_str_hub(i,1:n
ns_hub))),'--','Color',[0 191/255 1])

%####suction surface

%camberline coordinate at origin of the chord
y_orig_str_hub(i)=(chord_str(i)/2)*tand(theta_str_hub(i)/4);

dd_str_hub(i)=y_orig_str_hub(i)+tb_str_hub(i)/2-
r_0_str_hub(i)*sind(theta_str_hub(i)/2);
Rup_str_hub(i)=(dd_str_hub(i)^2-r_0_str_hub(i)^2+(chord_str(i)/2-
r_0_str_hub(i)*cosd(theta_str_hub(i)/2))^2)/(2*(dd_str_hub(i)-
r_0_str_hub(i)));

x_u_str_int1_hub(i)=-(chord_str(i)/2-
r_0_str_hub(i)*cosd(theta_str_hub(i)/2));
x_u_str_int2_hub(i)=(chord_str(i)/2-
r_0_str_hub(i)*cosd(theta_str_hub(i)/2));

if i==1

    x_u_str1_hub=[(x_u_str_int1_hub(i):0.001:x_u_str_int2_hub(i))];
    nn1_us_hub=length((x_u_str_int1_hub(i):0.001:x_u_str_int2_hub(i)));

else

    nn_us_hub=length((x_u_str_int1_hub(i):0.001:x_u_str_int2_hub(i)));

x_u_str1_hub=[x_u_str1_hub;[(x_u_str_int1_hub(i):0.001:x_u_str_int2_hub(i))
,zeros(1,nn1_us_hub-nn_us_hub)]];

end
```

```
clear x_u_str_hub
if i==1
    nn_us_hub=length((x_u_str_int1_hub(i):0.001:x_u_str_int2_hub(i)));
end
    x_u_str_hub=x_u_str1_hub(i,1:nn_us_hub);


y_u_orig_str_hub(i,1:nn_us_hub)=y_orig_str_hub(i)+tb_str_hub(i)/2-
Rup_str_hub(i);

y_u_str_hub(i,1:nn_us_hub)=y_u_orig_str_hub(i)+sqrt(Rup_str_hub(i)^2-
x_u_str_hub.^2);
x_u_s_str_hub(i,1:nn_us_hub)=x_u_str_hub*cosd(stagger_str_hub(i))-
y_u_str_hub(i,1:nn_us_hub)*sind(stagger_str_hub(i));
y_u_s_str_hub(i,1:nn_us_hub)=x_u_str_hub*sind(stagger_str_hub(i))+y_u_str_h
ub(i,1:nn_us_hub)*cosd(stagger_str_hub(i));


% suction surface plot


subplot(1,2,2);plot3(y_u_s_str_hub(i,1:nn_us_hub),-
x_u_s_str_hub(i,1:nn_us_hub),repmat(STG(i).r_hub_str,size(y_u_s_str_hub(i,1
:nn_us_hub))),'Color',[0 191/255 1])
axis([-0.02 0.02 -0.02 0.02 0.2 0.6])
%##pressure surface

tb_l_str_hub(i)=-tb_str_hub(i);
r_0_l_str_hub(i)=-r_0_str_hub(i);
dd_l_str_hub(i)=y_orig_str_hub(i)+tb_l_str_hub(i)/2-
r_0_l_str_hub(i)*sind(theta_str_hub(i)/2);
Rlo_str_hub(i)=(dd_l_str_hub(i)^2-r_0_l_str_hub(i)^2+(chord_str(i)/2-
r_0_l_str_hub(i)*cosd(theta_str_hub(i)/2))^2)/(2*(dd_l_str_hub(i)-
r_0_l_str_hub(i)));
theta_lo_str_hub(i)=2*asind(chord_str(i)/2-
r_0_l_str_hub(i)*cosd(theta_str_hub(i)/2))*(1/(Rlo_str_hub(i)-
r_0_l_str_hub(i)));

x_l_str_int1_hub(i)=-(chord_str(i)/2-
r_0_str_hub(i)*cosd(theta_str_hub(i)/2));
x_l_str_int2_hub(i)=(chord_str(i)/2-
r_0_str_hub(i)*cosd(theta_str_hub(i)/2));


if i==1

    x_l_str1_hub=[(x_l_str_int1_hub(i):0.001:x_l_str_int2_hub(i))];
    nn1_ls_hub=length((x_l_str_int1_hub(i):0.001:x_l_str_int2_hub(i)));

else

    nn_ls_hub=length((x_l_str_int1_hub(i):0.001:x_l_str_int2_hub(i)));

x_l_str1_hub=[x_l_str1_hub;[(x_l_str_int1_hub(i):0.001:x_l_str_int2_hub(i))
,zeros(1,nn1_ls_hub-nn_ls_hub)]];

end
```

```
clear x_l_str_hub
if i==1
    nn_ls_hub=length((x_l_str_int1_hub(i):0.001:x_l_str_int2_hub(i)));
end
    x_l_str_hub=x_l_str1_hub(i,1:nn_ls_hub);

y_l_orig_str_hub(i,1:nn_ls_hub)=y_orig_str_hub(i)+tb_l_str_hub(i)/2-
Rlo_str_hub(i);
% behaviour of pressure surface in y direction
y_l_str_hub(i,1:nn_ls_hub)=y_l_orig_str_hub(i,1:nn_ls_hub)+sqrt(Rlo_str_hub
(i)^2-x_l_str_hub.^2);
%staggered blade
x_l_s_str_hub(i,1:nn_ls_hub)=x_l_str_hub*cosd(stagger_str_hub(i))-
y_l_str_hub(i,1:nn_ls_hub)*sind(stagger_str_hub(i));
y_l_s_str_hub(i,1:nn_ls_hub)=x_l_str_hub*sind(stagger_str_hub(i))+y_l_str_h
ub(i,1:nn_ls_hub)*cosd(stagger_str_hub(i));


% pressure surface plot

subplot(1,2,2);plot3(y_l_s_str_hub(i,1:nn_ls_hub),-
x_l_s_str_hub(i,1:nn_ls_hub),repmat(STG(i).r_hub_str,size(y_l_s_str_hub(i,1
:nn_ls_hub))),'Color',[0 191/255 1])

% nose design
y_n_str_hub(i)=r_0_str_hub(i)*sind(theta_str_hub(i)/2);
x_n1_str_hub(i)=-(chord_str(i)/2-r_0_str_hub(i)*cosd(theta_str_hub(i)/2));
x_n2_str_hub(i)=chord_str(i)/2-r_0_str_hub(i)*cosd(theta_str_hub(i)/2);
ang1=0:0.001:2*pi;
xp_str_hub=r_0_str_hub(i)*cos(ang1);
yp_str_hub=r_0_str_hub(i)*sin(ang1);

x_n1_s_str_hub(i)=x_n1_str_hub(i)*cosd(stagger_str_hub(i))-
y_n_str_hub(i)*sind(stagger_str_hub(i));
x_n2_s_str_hub(i)=x_n2_str_hub(i)*cosd(stagger_str_hub(i))-
y_n_str_hub(i)*sind(stagger_str_hub(i));
y_n1_s_str_hub(i)=x_n1_str_hub(i)*sind(stagger_str_hub(i))+y_n_str_hub(i)*c
osd(stagger_str_hub(i));
y_n2_s_str_hub(i)=x_n2_str_hub(i)*sind(stagger_str_hub(i))+y_n_str_hub(i)*c
osd(stagger_str_hub(i));

% nose plot
% plot(y_n1_s_str(i)+yp_str,x_n1_s_str(i)+xp_str-axial_spc(i),'b')
% plot(y_n2_s_str(i)+yp_str,x_n2_s_str(i)+xp_str-axial_spc(i),'b')
% plot(y_n1_s_str(i)+spacing_str(i)+yp_str,x_n1_s_str(i)+xp_str-
axial_spc(i),'b')
% plot(y_n1_s_str(i)-spacing_str(i)+yp_str,x_n1_s_str(i)+xp_str-
axial_spc(i),'b')
% plot(y_n2_s_str(i)+spacing_str(i)+yp_str,x_n2_s_str(i)+xp_str-
axial_spc(i),'b')
% plot(y_n2_s_str(i)-spacing_str(i)+yp_str,x_n2_s_str(i)+xp_str-
axial_spc(i),'b')
subplot(1,2,2);plot3(y_n1_s_str_hub(i)+yp_str_hub,-
x_n1_s_str_hub(i)+xp_str_hub,repmat(STG(i).r_hub_str,size(y_n1_s_str_hub(i)
+yp_str_hub)),'Color',[0 191/255 1]);
```

```
subplot(1,2,2);plot3(y_n2_s_str_hub(i)+yp_str_hub,-
x_n2_s_str_hub(i)+xp_str_hub,repmat(STG(i).r_hub_str,size(y_n2_s_str_hub(i)
+yp_str_hub)),'Color',[0 191/255 1]);

% ##### TIP

if proj_law == 'FoV'
    theta_str_tip(i)= STG(i).camber_angle_str_FV_tip;
    stagger_str_tip(i)=- STG(i).stagger_angle_str_FV_tip;
    tb_str_tip(i)=STG(i).TONC_str.*chord_str(i);
    r_0_str_tip(i)=0.1.*tb_str_tip(i);

elseif proj_law == 'MFV'
    theta_str_tip(i)= STG(i).camber_angle_str_FREEV_tip;
    stagger_str_tip(i)= -STG(i).stagger_angle_str_FREEV_tip;
    tb_str_tip(i)=STG(i).TONC_str.*chord_str(i);
    r_0_str_tip(i)=0.1.*tb_str_tip(i);
end

%radius of curvature
R_c_str_tip(i)=chord_str(i)*1./(2*sind(theta_str_tip(i)./2));

%origin of curvature
orig_c_str_tip(i)=-R_c_str_tip(i)*cosd(theta_str_tip(i)./2);

%chord in x


if i==1

    x_c_str1_tip=[(-chord_str(i)/2:0.001:chord_str(i)/2)];
    nn1s_tip=length((-chord_str(i)/2:0.001:chord_str(i)/2));
else

    nns_tip=length((-chord_str(i)/2:0.001:chord_str(i)/2));
    x_c_str1_tip=[x_c_str1_tip;[(-
chord_str(i)/2:0.001:chord_str(i)/2),zeros(1,nn1s_tip-nns_tip)]];
end

clear x_c_str_tip
if i==1
    nns_tip=length((-chord_str(i)/2:0.001:chord_str(i)/2));
end
    x_c_str_tip=x_c_str1_tip(i,1:nns_tip);

% behaviour of chord in y direction
y_c_str_tip(i,1:nns_tip)=orig_c_str_tip(i)+sqrt(R_c_str_tip(i)^2-
x_c_str_tip.^2);
%staggered blade
x_c_s_str_tip(i,1:nns_tip)=x_c_str_tip.*cosd(stagger_str_tip(i))-
y_c_str_tip(i,1:nns_tip).*sind(stagger_str_tip(i));% sign of y changed
y_c_s_str_tip(i,1:nns_tip)=x_c_str_tip.*sind(stagger_str_tip(i))+y_c_str_ti
p(i,1:nns_tip).*cosd(stagger_str_tip(i));

%chord plot
subplot(1,2,2);plot3(y_c_s_str_tip(i,1:nns_tip),-
x_c_s_str_tip(i,1:nns_tip),repmat(STG(i).r_tip_str,size(y_c_s_str_tip(i,1:n
ns_tip))),'--','Color',[16/255 78/255 139/255])
```

```
%####suction surface

%camberline coordinate at origin of the chord
y_orig_str_tip(i)=(chord_str(i)/2)*tand(theta_str_tip(i)/4);

dd_str_tip(i)=y_orig_str_tip(i)+tb_str_tip(i)/2-
r_0_str_tip(i)*sind(theta_str_tip(i)/2);
Rup_str_tip(i)=(dd_str_tip(i)^2-r_0_str_tip(i)^2+(chord_str(i)/2-
r_0_str_tip(i)*cosd(theta_str_tip(i)/2))^2)/(2*(dd_str_tip(i)-
r_0_str_tip(i)));

x_u_str_int1_tip(i)=-(chord_str(i)/2-
r_0_str_tip(i)*cosd(theta_str_tip(i)/2));
x_u_str_int2_tip(i)=(chord_str(i)/2-
r_0_str_tip(i)*cosd(theta_str_tip(i)/2));

if i==1

    x_u_str1_tip=[(x_u_str_int1_tip(i):0.001:x_u_str_int2_tip(i))];
    nn1_us_tip=length((x_u_str_int1_tip(i):0.001:x_u_str_int2_tip(i)));

else

    nn_us_tip=length((x_u_str_int1_tip(i):0.001:x_u_str_int2_tip(i)));

x_u_str1_tip=[x_u_str1_tip;[(x_u_str_int1_tip(i):0.001:x_u_str_int2_tip(i))
,zeros(1,nn1_us_tip-nn_us_tip)]];

end

clear x_u_str_tip
if i==1
    nn_us_tip=length((x_u_str_int1_tip(i):0.001:x_u_str_int2_tip(i)));
end
    x_u_str_tip=x_u_str1_tip(i,1:nn_us_tip);


y_u_orig_str_tip(i,1:nn_us_tip)=y_orig_str_tip(i)+tb_str_tip(i)/2-
Rup_str_tip(i);

y_u_str_tip(i,1:nn_us_tip)=y_u_orig_str_tip(i)+sqrt(Rup_str_tip(i)^2-
x_u_str_tip.^2);
x_u_s_str_tip(i,1:nn_us_tip)=x_u_str_tip*cosd(stagger_str_tip(i))-
y_u_str_tip(i,1:nn_us_tip)*sind(stagger_str_tip(i));
y_u_s_str_tip(i,1:nn_us_tip)=x_u_str_tip*sind(stagger_str_tip(i))+y_u_str_t
ip(i,1:nn_us_tip)*cosd(stagger_str_tip(i));


% suction surface plot


subplot(1,2,2);plot3(y_u_s_str_tip(i,1:nn_us_tip),-
x_u_s_str_tip(i,1:nn_us_tip),repmat(STG(i).r_tip_str,size(y_u_s_str_tip(i,1
:nn_us_tip))),'Color',[16/255 78/255 139/255])

%##pressure surface

tb_l_str_tip(i)=-tb_str_tip(i);
```

```
r_0_l_str_tip(i)=-r_0_str_tip(i);
dd_l_str_tip(i)=y_orig_str_tip(i)+tb_l_str_tip(i)/2-
r_0_l_str_tip(i)*sind(theta_str_tip(i)/2);
Rlo_str_tip(i)=(dd_l_str_tip(i)^2-r_0_l_str_tip(i)^2+(chord_str(i)/2-
r_0_l_str_tip(i)*cosd(theta_str_tip(i)/2))^2)/(2*(dd_l_str_tip(i)-
r_0_l_str_tip(i)));
theta_lo_str_tip(i)=2*asind(chord_str(i)/2-
r_0_l_str_tip(i)*cosd(theta_str_tip(i)/2))*(1/(Rlo_str_tip(i)-
r_0_l_str_tip(i)));

x_l_str_int1_tip(i)=-(chord_str(i)/2-
r_0_str_tip(i)*cosd(theta_str_tip(i)/2));
x_l_str_int2_tip(i)=(chord_str(i)/2-
r_0_str_tip(i)*cosd(theta_str_tip(i)/2));


if i==1

    x_l_str1_tip=[(x_l_str_int1_tip(i):0.001:x_l_str_int2_tip(i))];
    nn1_ls_tip=length((x_l_str_int1_tip(i):0.001:x_l_str_int2_tip(i)));

else

    nn_ls_tip=length((x_l_str_int1_tip(i):0.001:x_l_str_int2_tip(i)));

x_l_str1_tip=[x_l_str1_tip;[(x_l_str_int1_tip(i):0.001:x_l_str_int2_tip(i))
,zeros(1,nn1_ls_tip-nn_ls_tip)]];

end




clear x_l_str_tip
if i==1
    nn_ls_tip=length((x_l_str_int1_tip(i):0.001:x_l_str_int2_tip(i)));
end
    x_l_str_tip=x_l_str1_tip(i,1:nn_ls_tip);

y_l_orig_str_tip(i,1:nn_ls_tip)=y_orig_str_tip(i)+tb_l_str_tip(i)/2-
Rlo_str_tip(i);
% behaviour of pressure surface in y direction
y_l_str_tip(i,1:nn_ls_tip)=y_l_orig_str_tip(i,1:nn_ls_tip)+sqrt(Rlo_str_tip
(i)^2-x_l_str_tip.^2);
%staggered blade
x_l_s_str_tip(i,1:nn_ls_tip)=x_l_str_tip*cosd(stagger_str_tip(i))-
y_l_str_tip(i,1:nn_ls_tip)*sind(stagger_str_tip(i));
y_l_s_str_tip(i,1:nn_ls_tip)=x_l_str_tip*sind(stagger_str_tip(i))+y_l_str_t
ip(i,1:nn_ls_tip)*cosd(stagger_str_tip(i));


% pressure surface plot

subplot(1,2,2);plot3(y_l_s_str_tip(i,1:nn_ls_tip),-
x_l_s_str_tip(i,1:nn_ls_tip),repmat(STG(i).r_tip_str,size(y_l_s_str_tip(i,1
:nn_ls_tip))),'Color',[16/255 78/255 139/255])

% nose design
```

```
y_n_str_tip(i)=r_0_str_tip(i)*sind(theta_str_tip(i)/2);
x_n1_str_tip(i)=-(chord_str(i)/2-r_0_str_tip(i)*cosd(theta_str_tip(i)/2));
x_n2_str_tip(i)=chord_str(i)/2-r_0_str_tip(i)*cosd(theta_str_tip(i)/2);
ang1=0:0.001:2*pi;
xp_str_tip=r_0_str_tip(i)*cos(ang1);
yp_str_tip=r_0_str_tip(i)*sin(ang1);

x_n1_s_str_tip(i)=x_n1_str_tip(i)*cosd(stagger_str_tip(i))-
y_n_str_tip(i)*sind(stagger_str_tip(i));
x_n2_s_str_tip(i)=x_n2_str_tip(i)*cosd(stagger_str_tip(i))-
y_n_str_tip(i)*sind(stagger_str_tip(i));
y_n1_s_str_tip(i)=x_n1_str_tip(i)*sind(stagger_str_tip(i))+y_n_str_tip(i)*c
osd(stagger_str_tip(i));
y_n2_s_str_tip(i)=x_n2_str_tip(i)*sind(stagger_str_tip(i))+y_n_str_tip(i)*c
osd(stagger_str_tip(i));

% nose plot

subplot(1,2,2);plot3(y_n1_s_str_tip(i)+yp_str_tip,-
x_n1_s_str_tip(i)+xp_str_tip,repmat(STG(i).r_tip_str,size(y_n1_s_str_tip(i)
+yp_str_tip)),'Color',[16/255 78/255 139/255]);
subplot(1,2,2);plot3(y_n2_s_str_tip(i)+yp_str_tip,-
x_n2_s_str_tip(i)+xp_str_tip,repmat(STG(i).r_tip_str,size(y_n2_s_str_tip(i)
+yp_str_tip)),'Color',[16/255 78/255 139/255]);

xlabel('[m]')
ylabel('[m]')
zlabel('[m]')
title(['Stator Shape for Stage Number:',num2str(i),])
grid on
axis equal
hold off
```

B5, Main Calculation

```
% Main Calculation for the compressor

%######################################################################
%##                                                                  ##
%##                        Main Calculation                          ##
%##                                                                  ##
%##             (c) Niclas Falck and Magnus Genrup                   ##
%##                     and Daniele Perrotti        (2013)           ##
%##                                                                  ##
%##             Lund University/Dept of Energy Sciences              ##
%##                                                                  ##
%######################################################################


function [STG,CompInfo,OGV] = compressorcalculation(filename)
globalvariables %call for the global variables

%################# Converts textfile to a matrix #########################

CompInputdata = createInputFile(filename);
```

```
%######################  Numerical settings  ##############################

RLX_REACT = 0.8;
RLX_PR = 0.95;

%################### Import data from the input matrix ####################


N_stg = str2num(CompInputdata{5,1}); % number of stages in the compressor

PR_comp = str2num(CompInputdata{7,1}); % sets the desirable compressor ratio

P0_in = str2num(CompInputdata{3,1}); % absolute inlet pressure
T0_in = str2num(CompInputdata{4,1})-273.15; % absolute inlet temperature
RPM = str2num(CompInputdata{8,1}); % revolutions per minute

for k=1:N_stg % massflow variation
    flow(k) = str2num(CompInputdata{6,k});
end

Alpha_in = str2num(CompInputdata{12,1});
PHI_in = str2num(CompInputdata{13,1});
HONT_in = str2num(CompInputdata{14,1}); % hub/tip

comp_type = CompInputdata{2,1};
SONC_type = CompInputdata{11,1};
set_REACT = str2num(CompInputdata{9,1});

proj_law = CompInputdata{27,1}; % project law choose
if  proj_law == 'MFV'
    n = CompInputdata{28,1}; %type of swirl law
end

% set initial C_OGV
if comp_type=='EHT'
    if proj_law == 'FoV'
       C_OGV_new = str2num(CompInputdata{28,1}) %  %C_OGV it's 131
    elseif proj_law == 'MFV'
        C_OGV_new = str2num(CompInputdata{29,1})
    end
end

if set_REACT == 1
    for i=1:N_stg
        REACT_stg(i) = str2num(CompInputdata{10,i}); % sets a fixed value of the
degree of reation
    end
end

for i=1:N_stg
    Whirl_angle(i)=str2num(CompInputdata{10,i});%whirl angle
    EPSONC_rtr(i) = str2num(CompInputdata{15,i}); %(blande end clearence)/chord
    EPSONC_str(i) = str2num(CompInputdata{16,i}); %(blande end clearence)/chord

    AR_rtr(i) = str2num(CompInputdata{17,i});   %Aspect ratio (H/C)
    AR_str(i) = str2num(CompInputdata{18,i});

    TONC_rtr(i) = str2num(CompInputdata{19,i}); % (T/C)
```

```
    TONC_str(i) = str2num(CompInputdata{20,i});

    if strcmp(SONC_type,'Custom') == 0  % SONC is not set but is calculated
instead
        DF_rtr(i) = str2num(CompInputdata{21,i});
        DF_str(i) = str2num(CompInputdata{22,i});
    else
        SONC_rtr(i) = str2num(CompInputdata{21,i});
        SONC_str(i) = str2num(CompInputdata{22,i});
    end

    AVR_rtr(i) = str2num(CompInputdata{23,i});  % Axial Velocity Ratio
    AVR_str(i) = str2num(CompInputdata{24,i});

    BLK_stg(i) = str2num(CompInputdata{25,i});  % Blockage Factor

    PSI_variation(i) = str2num(CompInputdata{26,i}); %loading distribution
end



%########################## Compressor inlet ##############################

[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',P0_in,T0_in,0,1);

Cp_in = Cp;
rho_in = rho;
Visc_in = Visc;
kappa_in = kappa;
a_in = a;

[r_rms_in, r_m_in, r_hub_in, r_tip_in] =
Inletgeom(P0_in,T0_in,flow(1),RPM,HONT_in,PHI_in,Alpha_in,BLK_stg(1));

U_in = r_rms_in*pi*RPM/30; %blade speed based om RMS radius
Cm_in = PHI_in*U_in; %meridional velocity
C_in = Cm_in/cosd(Alpha_in);
M_in = C_in/a_in; % inlet relative Mach #

U_tip_in = r_tip_in*pi*RPM/30;

M_tip_in = ((Cm_in^2+(U_tip_in-Cm_in*tand(Alpha_in))^2)^0.5)/a_in;

area_in = flow(1)/(Cm_in*rho_in);

if  comp_type=='EHT'
    EHT_rel_error_level=1;
    n_EHT=0;
    conv_EHT=0;
       while conv_EHT == 0 % Solves for correct pressure ratio

             if abs(EHT_rel_error_level) < 10^(-4)
                conv_EHT = 1;
             end

             if n_EHT==0
                T0_OGV_new=400;% guess value for outlet temperature
```

```
                [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto,
LHV, y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar,
y_He]=state('PT',P0_in*PR_comp,T0_OGV_new,0,1);
                 h_exit=H-C_OGV_new^2/2;

                [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto,
LHV, y_SO2, y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('HS',h_exit,S,0,1);

                 rho_OGV = rho;

             else
                 T0_OGV_new=T0_OGV;
                 C_OGV_new=C_OGV;
             end
    area_final=flow(N_stg)/(rho_OGV*C_OGV_new*BLK_stg(N_stg));
    area_eff=area_in-area_final;
    r_rms_out=sqrt(area_eff/pi);



    % % ################### PRESSURE########################

    PR_loop % call for the pressure loop

    % %#####################################################

    n_EHT=n_EHT+1;
    EHT_rel_error_level=1-T0_OGV/T0_OGV_new;
       end
else
      PR_loop
end

pressure_ratio = P_OGV/P01(1);

%########################### Blade angles ##################################

for i = 1:N_stg

    spacing_rtr(i) = chord_rtr(i)*SONC_rtr(i);
    diameter_rtr(i) = 2*pi*r_rms_rtr(i);
    numb_blades_rtr(i) = diameter_rtr(i)/spacing_rtr(i);
    numb_blades_rtr(i) = ceil(numb_blades_rtr(i));

    spacing_str(i) = chord_str(i)*SONC_str(i);
    diameter_str(i) = 2*pi*r_rms_str(i);
    numb_blades_str(i) = diameter_str(i)/spacing_str(i);
    numb_blades_str(i) = ceil(numb_blades_str(i));

    %############################## Rotor angles #########################
    rel_ang_in = Beta1(i);
    rel_ang_out = Beta2(i);
    SONC = SONC_rtr(i);
    TONC = TONC_rtr(i);
    M = MW1(i);
```

```
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,blade_a
ngle_in,blade_angle_out] = Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
    incidence_angle_rtr(i) = incidence_angle;
    deviation_angle_rtr(i) = deviation_angle;
    camber_angle_rtr(i) = camber_angle;
    attack_angle_rtr(i) = attack_angle;
    stagger_angle_rtr(i) = stagger_angle;
    blade_angle_in_rtr(i) = blade_angle_in;
    blade_angle_out_rtr(i) = blade_angle_out;



    %########################### Stator angles ############################
    rel_ang_in = Alpha2(i);
    rel_ang_out = Alpha3(i);
    SONC = SONC_str(i);
    TONC = TONC_str(i);
    M = MC2(i);

[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,blade_a
ngle_in,blade_angle_out] = Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
    incidence_angle_str(i) = incidence_angle;
    deviation_angle_str(i) = deviation_angle;
    camber_angle_str(i) = camber_angle;
    attack_angle_str(i) = attack_angle;
    stagger_angle_str(i) = stagger_angle;
    blade_angle_in_str(i) = blade_angle_in;
    blade_angle_out_str(i) = blade_angle_out;




    %########################### Tip-housing angle ########################

    tip_angle_rtr(i) = atand((r_tip_1(i)-
r_tip_2(i))/(chord_rtr(i)*cosd(stagger_angle_rtr(i))));
    tip_angle_str(i) = atand((r_tip_2(i)-
r_tip_3(i))/(chord_str(i)*cosd(stagger_angle_str(i))));

   if proj_law == 'FoV'
       Forced_Vortex_BA_DF_stg % call for the blade angles and diffusion factor
from Forced Vortex law
   elseif proj_law == 'MFV'
       Free_Vortex_BA_DF_stg
   end
end

%##################### Blade angles for the OGV ###########################

spacing_OGV = chord_OGV*SONC_OGV;
diameter_OGV = 2*pi*r_rms_OGV;
numb_blades_OGV = diameter_OGV/spacing_OGV;
numb_blades_OGV = ceil(numb_blades_OGV);

rel_ang_in = Alpha3(N_stg);
rel_ang_out = 0;
SONC = SONC_OGV;
TONC = TONC_str(N_stg);
```

```
M = MC3(N_stg);
[incidence_angle,deviation_angle,camber_angle,attack_angle,stagger_angle,blade_a
ngle_in,blade_angle_out] = Bladeangles(rel_ang_in,rel_ang_out,SONC,TONC,M);
incidence_angle_OGV = incidence_angle;
deviation_angle_OGV = deviation_angle;
camber_angle_OGV = camber_angle;
attack_angle_OGV = attack_angle;
stagger_angle_OGV = stagger_angle;
blade_angle_in_OGV = blade_angle_in;
blade_angle_out_OGV = blade_angle_out;


 if proj_law == 'FoV'
      Forced_Vortex_BA_DF_OGV % call for the blade angles and diffusion factor
from Forced Vortex law
  elseif proj_law == 'MFV'
       Free_Vortex_BA_DF_OGV
 end

%########################### Misc. properties ##############################

Power=0; %Resetting stage power summation

for i=1:N_stg

    %####################### static pressure rise ########################

    Cp_rtr(i) = (P2(i)-P1(i))/(P01_rel(i)-P1(i));
    Cp_str(i) = (P3(i)-P2(i))/(P02(i)-P2(i));

    %######################### Stage pressure ratio ######################

    PR_stg(i) = P03(i)/P01(i);

    %##################### Accumulated pressure ratio ###################

    PR_acc(i) = P03(i)/P01(1);

    %######################### Stage temp increase #######################

    dT0_stg(i) = T03(i)-T01(i);

    %################### Polytropic stage efficiency #####################

    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',1,T03(i),0,1);
    aa = S; % a dummie variable
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',1,T01(i),0,1);
    bb = S; % a dummie variable
    poly_eff_stg(i) = R*log(P03(i)/P01(i))/(aa-bb);

    %################ Accumulated polytropic efficiency ##################

    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',1,T03(i),0,1);
    aa = S; % a dummie variable
```

```
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',1,T01(1),0,1);
    bb = S; % a dummie variable
    poly_eff_acc(i) = R*log(P03(i)/P01(1))/(aa-bb);

    %###################### Isentropic stage efficiency ##################

    P = P03(i);
    S = S01(i);
    [P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PS',P,S,0,1);
    H03s = H; % the isentropic enthalpy
    isen_eff_stg(i) = (H03s-H01(i))/(H03(i)-H01(i));

    %##################### Stage flow coefficient #########################

    PHI_stg(i) = (Cm1(i)+Cm2(i))/(U1(i)+U2(i));

    %###################### Compressor Power  ############################

    Power=Power+flow(i)*(H03(i)-H01(i))/1000;

end

%############################ Stall and Surge ############################
%###########################################################################

for i =1:N_stg

    %##################### constants/variables #####################

    % staggered spacing
    g_rtr =
pi*r_rms_rtr(i)*(cosd(blade_angle_in_rtr(i))+cosd(blade_angle_out_rtr(i)))/numb_
blades_rtr(i);
    g_str =
pi*r_rms_str(i)*(cosd(blade_angle_in_str(i))+cosd(blade_angle_out_str(i)))/numb_
blades_str(i);

    g = (W1(i)^2*g_rtr + C2(i)^2*g_str)/(W1(i)^2+C2(i)^2); % average value of g
in the stage

    % L/g2, L is meanline length of circular-arc profile
    LONG2_rtr =
(1/SONC_rtr(i))/(cosd(blade_angle_out_rtr(i))*cosd(camber_angle_rtr(i)/2));
    LONG2_str =
(1/SONC_str(i))/(cosd(blade_angle_out_str(i))*cosd(camber_angle_str(i)/2));

    LONG2 = (W1(i)^2*LONG2_rtr + C2(i)^2*LONG2_str)/(W1(i)^2+C2(i)^2); % average
value of L/g2 in the stage

    % endwall space
    epsilon_rtr = EPSONC_rtr(i)*chord_rtr(i);
    epsilon_str = EPSONC_str(i)*chord_str(i);

    epsilon = (W1(i)^2*epsilon_rtr + C2(i)^2*epsilon_str)/(W1(i)^2+C2(i)^2);

    % epsilon/g
```

```
    EPSONG = epsilon/g;

    %Reynolds number
    Re = (W1(i)^2*Re_rtr(i) + C2(i)^2*2*Re_str(i))/(W1(i)^2+C2(i)^2);

    % axial spacing
    axial_spacing_rtr = 0.2*chord_rtr(i);
    axial_spacing_str = 0.2*chord_str(i);

    axial_spacing = (W1(i)^2*axial_spacing_rtr +
C2(i)^2*axial_spacing_str)/(W1(i)^2+C2(i)^2);
    dZ = axial_spacing;

    %staggered spacing
    s_rtr = spacing_rtr(i);
    s_str = spacing_str(i);

    s = (W1(i)^2*spacing_rtr(i) + C2(i)^2*spacing_str(i))/(W1(i)^2+C2(i)^2);
    dZONS = dZ/s; % dZ/s

    %################## F_ef #################

    % rotor
    U_in = U1(i);
    C_in = C1(i);
    W_rtr_in = W1(i);
    if (Alpha1(i)+Beta1(i)) >=  90
        V_min = C1(i)*sind(Alpha1(i)+Beta1(i));
    else
        V_min = C1(i);
    end
    F_ef_rtr = (1+2.5*V_min^2+0.5*U_in^2)/(4*C_in^2);

    % stator
    U_in = U2(i);
    C_in = C2(i);
    V_str_in = C2(i);
    if (Alpha2(i)+Beta2(i)) >=  90
        V_min = C2(i)*sind(Alpha2(i)+Beta2(i));
    else
        V_min = C2(i);
    end
    F_ef_str = (1+2.5*V_min^2+0.5*U_in^2)/(4*C_in^2);

    % average
    F_ef(i) = (W1(i)^2*F_ef_rtr + C2(i)^2*F_ef_str)/(W1(i)^2+C2(i)^2);

    %######################## ChD ###############################

    x = LONG2;

    %polynomial coefficients
    coeff_Ch_D = [0.001777942251246
                 -0.019627519528419
                  0.091687954954062
                 -0.251659185450453
                  0.491601357182957
                  0.076431045899622];
```

```
    Ch_D(i) = 0;

    for j=1:6
        Ch_D(i) = Ch_D(i)+coeff_Ch_D(j)*(x)^(6-j); % evaluate the polynomial
    end

    %######################## (Ch/ChD)_eps ###############################

    x = EPSONG; % epsilon/g

    %polynomial coefficients
    coeff_Ch_eps = [-53510.30317191636
                     22041.80905688297
                    -3381.24369820182
                     242.41566524838544
                    -10.098550480478846
                     1.216825975980701];

    Ch_eps(i) = 0;

    for j=1:6
        Ch_eps(i) = Ch_eps(i)+coeff_Ch_eps(j)*(x)^(6-j); % evaluate the
polynomial
    end

    %######################## (Ch/ChD)_dZ ###############################

    x = dZONS; % dZ/S

    %polynomial coefficients
    coeff_Ch_dZ = [0.514206502798114
                  -0.745186356821405
                  -0.221066436780794
                   0.960732185823537
                  -0.615664604922058
                   1.119049824148622];

    Ch_dZ(i) = 0;

    for j=1:6
        Ch_dZ(i) = Ch_dZ(i)+coeff_Ch_dZ(j)*(x)^(6-j); % evaluate the polynomial
    end

    %######################## (Cp/CpD)_Re ###############################

    x = Re;

    % coefficients
    a = -107.8;
    b = -0.6767;
    c = 1.041;

    Ch_Re(i) = a*x^b+c;

    %###################################################

    Ch_max(i) = F_ef(i)*Ch_D(i)*Ch_Re(i)*Ch_dZ(i)*Ch_eps(i);
```

```
  %#################### Ch #####################

  kappa_mean = (kappa1(i)+kappa3(i))/2;
  Cp_mean = (Cp1(i)+Cp3(i))/2;

  aa = Cp_mean*(T1(i)+273.15)*((P3(i)/P1(i))^((kappa_mean-1)/kappa_mean)-1);
  bb = (U2(i)^2-U1(i)^2)/2;
  cc = (W1(i)^2+C2(i)^2)/2;

  Ch(i) = (aa-bb)/cc;

  omega(i) = Ch(i)/Ch_max(i);

end

%########################## Polytropic efficency #########################

P_ref = 1; % a reference pressure for the calculation
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',P_ref,T03(N_stg),0,1);
aa = S; % a dummie variable
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PT',P_ref,T01(1),0,1);
bb = S; % a dummie variable

poly_eff = R*log(P03(N_stg)/P01(1))/(aa-bb);

%########################## Isentropic efficency #########################

P = P3(N_stg);
S = S3(1);
[P, T, H, S, Cp, rho, Visc, lambda, kappa, R, a, crit, FARsto, LHV, y_SO2,
y_H2O, y_CO2, y_N2, y_O2, y_Ar, y_He]=state('PS',P,S,0,1);
H2s = H; % the isentropic enthalpy

isen_eff = (H2s-H1(1))/(H3(N_stg)-H1(1));

%############################# Compressor cost ###########################

mean_diameter = r_rms_1(1)+r_rms_3(N_stg);

comp_cost = 1.13*2625*(N_stg^1.155 * PR_comp^0.775 * mean_diameter^0.489 +
14.25);

%########################### Compressor Length ###########################

Comp_length = 0;

for i=1:N_stg

    Comp_length = Comp_length + chord_rtr(i)*cosd(stagger_angle_rtr(i));
    Comp_length = Comp_length + chord_rtr(i)*0.2;
    Comp_length = Comp_length + chord_str(i)*cosd(stagger_angle_str(i));
    Comp_length = Comp_length + chord_str(i)*0.2;

end
Comp_length = Comp_length - chord_str(N_stg)*0.2;
```

```
Comp_angle = atand((r_tip_1(1)-r_tip_3(N_stg))/Comp_length);

%############ Creates a structure of a properties and values  #############

CompInfo.comp_name = CompInputdata{1,1};
CompInfo.type = comp_type;
CompInfo.P0_in = P0_in;
CompInfo.T0_in = T0_in;
CompInfo.PR_comp = PR_comp;
CompInfo.N_stg = N_stg;
CompInfo.RPM = RPM;
CompInfo.Alpha_in = Alpha_in;
CompInfo.PHI_in = PHI_in;
CompInfo.HONT_in = HONT_in;
CompInfo.poly_eff = poly_eff;
CompInfo.isen_eff = isen_eff;
CompInfo.comp_cost = comp_cost;
CompInfo.area_in = area_in;
CompInfo.M_tip_in = M_tip_in;
CompInfo.Power = Power;
CompInfo.Comp_length = Comp_length;
CompInfo.Comp_angle = Comp_angle;

OGV.Cm = Cm_OGV;
OGV.C = C_OGV;
OGV.H0 = H0_OGV;
OGV.H = H_OGV;
OGV.S = S_OGV;
OGV.P = P_OGV;
OGV.T = T_OGV;
OGV.Cp = Cp_OGV;
OGV.rho = rho_OGV;
OGV.Visc = Visc_OGV;
OGV.kappa = kappa_OGV;
OGV.a = a_OGV;
OGV.P0 = P0_OGV;
OGV.T0 = T0_OGV;
OGV.MCm = MCm_OGV;
OGV.MC = MC3(N_stg);
OGV.dH = dH_OGV;
OGV.r_rms = r_rms_OGV;
OGV.r_tip = r_tip_OGV;
OGV.r_hub = r_hub_OGV;
OGV.HONT = HONT_OGV;
OGV.height = height_OGV;
OGV.chord = chord_OGV;
OGV.Re = Re_OGV;
OGV.SONC = SONC_OGV;
OGV.DF_lbl = DF_lbl_OGV;
OGV.Deq_star_lbl = Deq_star_lbl_OGV;
OGV.Deq = Deq_OGV;
OGV.Deq_star_ks = Deq_star_ks_OGV;
OGV.Mcrit_Hearsey = Mcrit_Hearsey_OGV;
OGV.Mcrit_Sch = Mcrit_Sch_OGV;
OGV.OMEGA_p = OMEGA_p_OGV;
OGV.OMEGA_ew = OMEGA_ew_OGV;
OGV.numb_blades = numb_blades_OGV;
OGV.incidence_angle = incidence_angle_OGV;
OGV.deviation_angle = deviation_angle_OGV;
OGV.camber_angle = camber_angle_OGV;
```

```
OGV.attack_angle = attack_angle_OGV;
OGV.stagger_angle = stagger_angle_OGV;
OGV.blade_angle_in = blade_angle_in_OGV;
OGV.blade_angle_out = blade_angle_out_OGV;

if proj_law == 'FoV'   %Forced Vortex Law values

OGV.Cm_OGV_FV_hub=Cm_OGV_FV_hub;
OGV.Cm_OGV_FV_tip=Cm_OGV_FV_tip;
OGV.Cp_OGV_FV_hub=Cp_OGV_FV_hub;
OGV.Cp_OGV_FV_tip=Cp_OGV_FV_tip;
OGV.DF_lbl_OGV_FV_hub=DF_lbl_OGV_FV_hub;
OGV.DF_lbl_OGV_FV_tip=DF_lbl_OGV_FV_tip;
OGV.Deq_OGV_FV_hub=Deq_OGV_FV_hub;
OGV.Deq_OGV_FV_tip=Deq_OGV_FV_tip;
OGV.Deq_star_lbl_OGV_FV_hub=Deq_star_lbl_OGV_FV_hub;
OGV.Deq_star_lbl_OGV_FV_tip=Deq_star_lbl_OGV_FV_tip;
OGV.Deq_star_ks_OGV_FV_hub=Deq_star_ks_OGV_FV_hub;
OGV.Deq_star_ks_OGV_FV_tip=Deq_star_ks_OGV_FV_tip;
OGV.H0_OGV_FV_hub=H0_OGV_FV_hub;
OGV.H0_OGV_FV_tip=H0_OGV_FV_tip;
OGV.H_OGV_FV_hub=H_OGV_FV_hub;
OGV.H_OGV_FV_tip=H_OGV_FV_tip;
OGV.MC_OGV_FV_hub=MC_OGV_FV_hub;
OGV.MC_OGV_FV_tip=MC_OGV_FV_tip;
OGV.Mcrit_Hearsey_OGV_FV_hub=Mcrit_Hearsey_OGV_FV_hub;
OGV.Mcrit_Hearsey_OGV_FV_tip=Mcrit_Hearsey_OGV_FV_tip;
OGV.P0_OGV_FV_tip=P0_OGV_FV_tip;
OGV.P0_OGV_FV_hub=P0_OGV_FV_hub;
OGV.P_OGV_FV_hub=P_OGV_FV_hub;
OGV.P_OGV_FV_tip=P_OGV_FV_tip;
OGV.SONC_OGV_FV_hub=SONC_OGV_FV_hub;
OGV.SONC_OGV_FV_tip=SONC_OGV_FV_tip;
OGV.T0_OGV_FV_tip=T0_OGV_FV_tip;
OGV.T0_OGV_FV_hub=T0_OGV_FV_hub;
OGV.T_OGV_FV_hub=T_OGV_FV_hub;
OGV.T_OGV_FV_tip=T_OGV_FV_tip;
OGV.SONC_OGV_FV_hub=SONC_OGV_FV_hub;
OGV.SONC_OGV_FV_tip=SONC_OGV_FV_tip;
OGV.a_OGV_FV_hub=a_OGV_FV_hub;
OGV.a_OGV_FV_tip=a_OGV_FV_tip;
OGV.blade_angle_in_OGV_FV_hub=blade_angle_in_OGV_FV_hub;
OGV.blade_angle_in_OGV_FV_tip=blade_angle_in_OGV_FV_tip;
OGV.blade_angle_out_OGV_FV_hub=blade_angle_out_OGV_FV_hub;
OGV.blade_angle_out_OGV_FV_tip=blade_angle_out_OGV_FV_tip;
OGV.camber_angle_OGV_FV_hub=camber_angle_OGV_FV_hub;
OGV.camber_angle_OGV_FV_tip=camber_angle_OGV_FV_tip;
OGV.deviation_angle_OGV_FV_hub=deviation_angle_OGV_FV_hub;
OGV.deviation_angle_OGV_FV_tip=deviation_angle_OGV_FV_tip;
OGV.dH_OGV_FV_hub=dH_OGV_FV_hub;
OGV.dH_OGV_FV_tip=dH_OGV_FV_tip;
OGV.incidence_angle_OGV_FV_hub=incidence_angle_OGV_FV_hub;
OGV.incidence_angle_OGV_FV_tip=incidence_angle_OGV_FV_tip;
OGV.rho_OGV_FV_hub=rho_OGV_FV_hub;
OGV.rho_OGV_FV_tip=rho_OGV_FV_tip;
OGV.stagger_angle_OGV_FV_hub=stagger_angle_OGV_FV_hub;
OGV.stagger_angle_OGV_FV_tip=stagger_angle_OGV_FV_tip;

elseif proj_law == 'MFV' % Modified Free Vortex Law Values

OGV.Cm_OGV_FREEV_hub=Cm_OGV_FREEV_hub;
```

```
  OGV.Cm_OGV_FREEV_tip=Cm_OGV_FREEV_tip;
  OGV.Cp_OGV_FREEV_hub=Cp_OGV_FREEV_hub;
  OGV.Cp_OGV_FREEV_tip=Cp_OGV_FREEV_tip;
  OGV.DF_lbl_OGV_FREEV_hub=DF_lbl_OGV_FREEV_hub;
  OGV.DF_lbl_OGV_FREEV_tip=DF_lbl_OGV_FREEV_tip;
  OGV.Deq_OGV_FREEV_hub=Deq_OGV_FREEV_hub;
  OGV.Deq_OGV_FREEV_tip=Deq_OGV_FREEV_tip;
  OGV.Deq_star_lbl_OGV_FREEV_hub=Deq_star_lbl_OGV_FREEV_hub;
  OGV.Deq_star_lbl_OGV_FREEV_tip=Deq_star_lbl_OGV_FREEV_tip;
  OGV.Deq_star_ks_OGV_FREEV_hub=Deq_star_ks_OGV_FREEV_hub;
  OGV.Deq_star_ks_OGV_FREEV_tip=Deq_star_ks_OGV_FREEV_tip;
  OGV.H0_OGV_FREEV_hub=H0_OGV_FREEV_hub;
  OGV.H0_OGV_FREEV_tip=H0_OGV_FREEV_tip;
  OGV.H_OGV_FREEV_hub=H_OGV_FREEV_hub;
  OGV.H_OGV_FREEV_tip=H_OGV_FREEV_tip;
  OGV.MC_OGV_FREEV_hub=MC_OGV_FREEV_hub;
  OGV.MC_OGV_FREEV_tip=MC_OGV_FREEV_tip;
  OGV.Mcrit_Hearsey_OGV_FREEV_hub=Mcrit_Hearsey_OGV_FREEV_hub;
  OGV.Mcrit_Hearsey_OGV_FREEV_tip=Mcrit_Hearsey_OGV_FREEV_tip;
  OGV.P0_OGV_FREEV_tip=P0_OGV_FREEV_tip;
  OGV.P0_OGV_FREEV_hub=P0_OGV_FREEV_hub;
  OGV.P_OGV_FREEV_hub=P_OGV_FREEV_hub;
  OGV.P_OGV_FREEV_tip=P_OGV_FREEV_tip;
  OGV.SONC_OGV_FREEV_hub=SONC_OGV_FREEV_hub;
  OGV.SONC_OGV_FREEV_tip=SONC_OGV_FREEV_tip;
  OGV.T0_OGV_FREEV_tip=T0_OGV_FREEV_tip;
  OGV.T0_OGV_FREEV_hub=T0_OGV_FREEV_hub;
  OGV.T_OGV_FREEV_hub=T_OGV_FREEV_hub;
  OGV.T_OGV_FREEV_tip=T_OGV_FREEV_tip;
  OGV.SONC_OGV_FREEV_hub=SONC_OGV_FREEV_hub;
  OGV.SONC_OGV_FREEV_tip=SONC_OGV_FREEV_tip;
  OGV.a_OGV_FREEV_hub=a_OGV_FREEV_hub;
  OGV.a_OGV_FREEV_tip=a_OGV_FREEV_tip;
  OGV.blade_angle_in_OGV_FREEV_hub=blade_angle_in_OGV_FREEV_hub;
  OGV.blade_angle_in_OGV_FREEV_tip=blade_angle_in_OGV_FREEV_tip;
  OGV.blade_angle_out_OGV_FREEV_hub=blade_angle_out_OGV_FREEV_hub;
  OGV.blade_angle_out_OGV_FREEV_tip=blade_angle_out_OGV_FREEV_tip;
  OGV.camber_angle_OGV_FREEV_hub=camber_angle_OGV_FREEV_hub;
  OGV.camber_angle_OGV_FREEV_tip=camber_angle_OGV_FREEV_tip;
  OGV.deviation_angle_OGV_FREEV_hub=deviation_angle_OGV_FREEV_hub;
  OGV.deviation_angle_OGV_FREEV_tip=deviation_angle_OGV_FREEV_tip;
  OGV.dH_OGV_FREEV_hub=dH_OGV_FREEV_hub;
  OGV.dH_OGV_FREEV_tip=dH_OGV_FREEV_tip;
  OGV.incidence_angle_OGV_FREEV_hub=incidence_angle_OGV_FREEV_hub;
  OGV.incidence_angle_OGV_FREEV_tip=incidence_angle_OGV_FREEV_tip;
  OGV.rho_OGV_FREEV_hub=rho_OGV_FREEV_hub;
  OGV.rho_OGV_FREEV_tip=rho_OGV_FREEV_tip;
  OGV.stagger_angle_OGV_FREEV_hub=stagger_angle_OGV_FREEV_hub;
  OGV.stagger_angle_OGV_FREEV_tip=stagger_angle_OGV_FREEV_tip;

end


for i = 1:N_stg

    STG(i).Alpha1 = Alpha1(i);
    STG(i).Alpha2 = Alpha2(i);
    STG(i).Alpha3 = Alpha3(i);
    STG(i).Beta1 = Beta1(i);
    STG(i).Beta2 = Beta2(i);
    STG(i).C1 = C1(i);
```

```
STG(i).C2 = C2(i);
STG(i).C3 = C3(i);
STG(i).W1 = W1(i);
STG(i).W2 = W2(i);
STG(i).Cm1 = Cm1(i);
STG(i).Cm2 = Cm2(i);
STG(i).Cm3 = Cm3(i);
STG(i).U1 = U1(i);
STG(i).U2 = U2(i);
STG(i).C_theta1 = C_theta1(i);
STG(i).C_theta2 = C_theta2(i);
STG(i).C_theta3 = C_theta3(i);
STG(i).W_theta1 = W_theta1(i);
STG(i).W_theta2 = W_theta2(i);
STG(i).MW1 = MW1(i);
STG(i).MC2 = MC2(i);
STG(i).Mcrit_Hearsey_rtr = Mcrit_Hearsey_rtr(i);
STG(i).Mcrit_Sch_rtr = Mcrit_Sch_rtr(i);
STG(i).Mcrit_Hearsey_str = Mcrit_Hearsey_str(i);
STG(i).Mcrit_Sch_str = Mcrit_Sch_str(i);
STG(i).a1 = a1(i);
STG(i).a2 = a2(i);
STG(i).a3 = a3(i);
STG(i).kappa1 = kappa1(i);
STG(i).kappa2 = kappa2(i);
STG(i).kappa3 = kappa3(i);
STG(i).Cp1 = Cp1(i);
STG(i).Cp2 = Cp2(i);
STG(i).Cp3 = Cp3(i);
STG(i).rho1 = rho1(i);
STG(i).rho2 = rho2(i);
STG(i).rho3 = rho3(i);
STG(i).visc1 = Visc1(i);
STG(i).visc2 = Visc2(i);
STG(i).visc3 = Visc3(i);
STG(i).P1 = P1(i);
STG(i).P2 = P2(i);
STG(i).P3 = P3(i);
STG(i).P01 = P01(i);
STG(i).P02 = P02(i);
STG(i).P03 = P03(i);
STG(i).T1 = T1(i);
STG(i).T2 = T2(i);
STG(i).T3 = T3(i);
STG(i).T01 = T01(i);
STG(i).T02 = T02(i);
STG(i).T03 = T03(i);
STG(i).H1 = H1(i);
STG(i).H2 = H2(i);
STG(i).H3 = H3(i);
STG(i).H01 = H01(i);
STG(i).H02 = H02(i);
STG(i).H03 = H03(i);
STG(i).S1 = S1(i);
STG(i).S2 = S2(i);
STG(i).S3 = S3(i);
STG(i).S01 = S1(i);
STG(i).S02 = S2(i);
STG(i).S03 = S3(i);
STG(i).EPSONC_rtr = EPSONC_rtr(i);
STG(i).EPSONC_str = EPSONC_str(i);
```

```
STG(i).SONC_rtr = SONC_rtr(i);
STG(i).SONC_str = SONC_str(i);
STG(i).HONT_rtr = HONT_rtr(i);
STG(i).HONT_str = HONT_str(i);
STG(i).TONC_rtr = TONC_rtr(i);
STG(i).TONC_str = TONC_str(i);
STG(i).AR_rtr = AR_rtr(i);
STG(i).AR_str = AR_str(i);
STG(i).chord_rtr = chord_rtr(i);
STG(i).chord_str = chord_str(i);
STG(i).height_rtr = height_rtr(i);
STG(i).height_str = height_str(i);
STG(i).DF_rtr = DF_lbl_rtr(i);
STG(i).DF_str = DF_lbl_str(i);
STG(i).Deq_rtr = Deq_rtr(i);
STG(i).Deq_str = Deq_str(i);
STG(i).Deq_star_lbl_rtr = Deq_star_lbl_rtr(i);
STG(i).Deq_star_lbl_str = Deq_star_lbl_str(i);
STG(i).Deq_star_ks_rtr = Deq_star_ks_rtr(i);
STG(i).Deq_star_ks_str = Deq_star_ks_str(i);
STG(i).dH_rtr = dH_rtr(i);
STG(i).dH_str = dH_str(i);
STG(i).dS_rtr = dS21(i);
STG(i).dS_str = dS32(i);
STG(i).area1 = area1(i);
STG(i).area2 = area2(i);
STG(i).area3 = area3(i);
STG(i).Re_rtr = Re_rtr(i);
STG(i).Re_str = Re_str(i);
STG(i).r_tip_1 = r_tip_1(i);
STG(i).r_tip_2 = r_tip_2(i);
STG(i).r_tip_3 = r_tip_3(i);
STG(i).r_hub_1 = r_hub_1(i);
STG(i).r_hub_2 = r_hub_2(i);
STG(i).r_hub_3 = r_hub_3(i);
STG(i).r_rms_1 = r_rms_1(i);
STG(i).r_rms_2 = r_rms_2(i);
STG(i).r_rms_3 = r_rms_3(i);
STG(i).r_hub_rtr = r_hub_rtr(i);
STG(i).r_tip_rtr = r_tip_rtr(i);
STG(i).r_hub_str = r_hub_str(i);
STG(i).r_tip_str = r_tip_str(i);
STG(i).r_rms_rtr = r_rms_rtr(i);
STG(i).r_rms_str = r_rms_str(i);

STG(i).incidence_angle_rtr = incidence_angle_rtr(i);
STG(i).deviation_angle_rtr = deviation_angle_rtr(i);
STG(i).camber_angle_rtr = camber_angle_rtr(i);
STG(i).attack_angle_rtr = attack_angle_rtr(i);
STG(i).stagger_angle_rtr = stagger_angle_rtr(i);
STG(i).turning_rtr = Beta1(i)-Beta2(i);
STG(i).blade_angle_in_rtr = blade_angle_in_rtr(i);
STG(i).blade_angle_out_rtr = blade_angle_out_rtr(i);
STG(i).chord_rtr = chord_rtr(i);
STG(i).incidence_angle_str = incidence_angle_str(i);
STG(i).deviation_angle_str = deviation_angle_str(i);
STG(i).camber_angle_str = camber_angle_str(i);
STG(i).attack_angle_str = attack_angle_str(i);
STG(i).stagger_angle_str = stagger_angle_str(i);
STG(i).turning_str = Alpha2(i)-Alpha3(i);
STG(i).blade_angle_in_str = blade_angle_in_str(i);
```

```
STG(i).blade_angle_out_str = blade_angle_out_str(i);
STG(i).tip_angle_rtr = tip_angle_rtr(i);
STG(i).tip_angle_str = tip_angle_str(i);
STG(i).spacing_rtr = spacing_rtr(i);
STG(i).numb_blades_rtr = numb_blades_rtr(i);
STG(i).spacing_str = spacing_str(i);
STG(i).numb_blades_str = numb_blades_str(i);

STG(i).PR = PR_stg(i);
STG(i).PR_acc = PR_acc(i);
STG(i).React = REACT_stg(i);
STG(i).PSI = PSI(1,i);
STG(i).PHI = PHI_stg(i);
STG(i).dT0 = dT0_stg(i);
STG(i).dS = dS21(i)+dS32(i);
STG(i).OMEGA_p_rtr = OMEGA_p_rtr(i);
STG(i).OMEGA_ew_rtr = OMEGA_ew_rtr(i);
STG(i).OMEGA_p_str = OMEGA_p_str(i);
STG(i).OMEGA_ew_str = OMEGA_ew_str(i);
STG(i).poly_eff = poly_eff_stg(i);
STG(i).poly_eff_acc = poly_eff_acc(i);
STG(i).isen_eff = isen_eff_stg(i);
STG(i).flow = flow(i);
STG(i).Ch = Ch(i);
STG(i).Ch_max = Ch_max(i);
STG(i).omega = omega(i);
%Blockage factor added by (c) Johannes Müller, February 2009
STG(i).BLK = BLK_stg(i);



 if proj_law == 'FoV'  %Forced Vortex Law values


STG(i).Alpha1_FV_hub=Alpha1_FV_hub(i);
STG(i).Alpha1_FV_tip=Alpha1_FV_tip(i);
STG(i).Alpha2=Alpha2(i);
STG(i).Alpha2_FV_hub=Alpha2_FV_hub(i);
STG(i).Alpha2_FV_tip=Alpha2_FV_tip(i);
STG(i).Alpha3=Alpha3(i);
STG(i).Alpha3_FV_hub=Alpha3_FV_hub(i);
STG(i).Alpha3_FV_tip=Alpha3_FV_tip(i);
STG(i).Beta1_FV_hub=Beta1_FV_hub(i);
STG(i).Beta1_FV_tip=Beta1_FV_tip(i);
STG(i).Beta2_FV_hub=Beta2_FV_hub(i);
STG(i).Beta2_FV_tip=Beta2_FV_tip(i);
STG(i).C1_FV_hub=C1_FV_hub(i);
STG(i).C1_FV_tip=C1_FV_tip(i);
STG(i).C2_FV_hub=C2_FV_hub(i);
STG(i).C2_FV_tip=C2_FV_tip(i);
STG(i).C3_FV_hub=C3_FV_hub(i);
STG(i).C3_FV_tip=C3_FV_tip(i);
STG(i).C_theta1_FV_hub=C_theta1_FV_hub(i);
STG(i).C_theta1_FV_tip=C_theta1_FV_tip(i);
STG(i).C_theta2_FV_hub=C_theta2_FV_hub(i);
STG(i).C_theta2_FV_tip=C_theta2_FV_tip(i);
STG(i).C_theta3_FV_hub=C_theta3_FV_hub(i);
STG(i).C_theta3_FV_tip=C_theta3_FV_tip(i);
STG(i).Cm1_FV_hub=Cm1_FV_hub(i);
STG(i).Cm1_FV_tip=Cm1_FV_tip(i);
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STG(i).Cm2_FV_hub=Cm2_FV_hub(i);
STG(i).Cm2_FV_tip=Cm2_FV_tip(i);
STG(i).Cm3_FV_hub=Cm3_FV_hub(i);
STG(i).Cm3_FV_tip=Cm3_FV_tip(i);
STG(i).Cp1_FV_hub=Cp1_FV_hub(i);
STG(i).Cp1_FV_tip=Cp1_FV_tip(i);
STG(i).Cp2_FV_hub=Cp2_FV_hub(i);
STG(i).Cp2_FV_tip=Cp2_FV_tip(i);
STG(i).Cp3_FV_hub=Cp3_FV_hub(i);
STG(i).Cp3_FV_tip=Cp3_FV_tip(i);
STG(i).DF_lbl_rtr_FV_hub=DF_lbl_rtr_FV_hub(i);
STG(i).DF_lbl_rtr_FV_tip=DF_lbl_rtr_FV_tip(i);
STG(i).DF_lbl_str_FV_hub=DF_lbl_str_FV_hub(i);
STG(i).DF_lbl_str_FV_tip=DF_lbl_str_FV_tip(i);
STG(i).Deq_rtr_FV_hub=Deq_rtr_FV_hub(i);
STG(i).Deq_rtr_FV_tip=Deq_rtr_FV_tip(i);
STG(i).Deq_star_ks_rtr_FV_hub=Deq_star_ks_rtr_FV_hub(i);
STG(i).Deq_star_ks_rtr_FV_tip=Deq_star_ks_rtr_FV_tip(i);
STG(i).Deq_star_ks_str_FV_hub=Deq_star_ks_str_FV_hub(i);
STG(i).Deq_star_ks_str_FV_tip=Deq_star_ks_str_FV_tip(i);
STG(i).Deq_star_lbl_rtr_FV_hub=Deq_star_lbl_rtr_FV_hub(i);
STG(i).Deq_star_lbl_rtr_FV_tip=Deq_star_lbl_rtr_FV_tip(i);
STG(i).Deq_star_lbl_str_FV_hub=Deq_star_lbl_str_FV_hub(i);
STG(i).Deq_star_lbl_str_FV_tip=Deq_star_lbl_str_FV_tip(i);
STG(i).Deq_str_FV_hub=Deq_str_FV_hub(i);
STG(i).Deq_str_FV_tip=Deq_str_FV_tip(i);
STG(i).H01_FV_hub=H01_FV_hub(i);
STG(i).H01_FV_tip=H01_FV_tip(i);
STG(i).H02_FV_hub=H02_FV_hub(i);
STG(i).H02_FV_tip=H02_FV_tip(i);
STG(i).H03_FV_hub=H03_FV_hub(i);
STG(i).H03_FV_tip=H03_FV_tip(i);
STG(i).H1_FV_hub=H1_FV_hub(i);
STG(i).H1_FV_tip=H1_FV_tip(i);
STG(i).H2_FV_hub=H2_FV_hub(i);
STG(i).H2_FV_tip=H2_FV_tip(i);
STG(i).H3_FV_hub=H3_FV_hub(i);
STG(i).H3_FV_tip=H3_FV_tip(i);
STG(i).MC2_FV_hub=MC2_FV_hub(i);
STG(i).MC2_FV_tip=MC2_FV_tip(i);
STG(i).MW1_FV_hub=MW1_FV_hub(i);
STG(i).MW1_FV_tip=MW1_FV_tip(i);
STG(i).Mcrit_Hearsey_rtr_FV_hub=Mcrit_Hearsey_rtr_FV_hub(i);
STG(i).Mcrit_Hearsey_rtr_FV_tip=Mcrit_Hearsey_rtr_FV_tip(i);
STG(i).Mcrit_Hearsey_str_FV_hub=Mcrit_Hearsey_str_FV_hub(i);
STG(i).Mcrit_Hearsey_str_FV_tip=Mcrit_Hearsey_str_FV_tip(i);
STG(i).P01_FV_hub=P01_FV_hub(i);
STG(i).P01_FV_tip=P01_FV_tip(i);
STG(i).P02_FV_hub=P02_FV_hub(i);
STG(i).P02_FV_tip=P02_FV_tip(i);
STG(i).P03_FV_hub=P03_FV_hub(i);
STG(i).P03_FV_tip=P03_FV_tip(i);
STG(i).P1_FV_hub=P1_FV_hub(i);
STG(i).P1_FV_tip=P1_FV_tip(i);
STG(i).P2_FV_hub=P2_FV_hub(i);
STG(i).P2_FV_tip=P2_FV_tip(i);
STG(i).P3_FV_hub=P3_FV_hub(i);
STG(i).P3_FV_tip=P3_FV_tip(i);
STG(i).SONC_rtr_FV_hub=SONC_rtr_FV_hub(i);
STG(i).SONC_rtr_FV_tip=SONC_rtr_FV_tip(i);
STG(i).SONC_str_FV_hub=SONC_str_FV_hub(i);
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STG(i).SONC_str_FV_tip=SONC_str_FV_tip(i);
STG(i).T01_FV_hub=T01_FV_hub(i);
STG(i).T01_FV_tip=T01_FV_tip(i);
STG(i).T02_FV_hub=T02_FV_hub(i);
STG(i).T02_FV_tip=T02_FV_tip(i);
STG(i).T03_FV_hub=T03_FV_hub(i);
STG(i).T03_FV_tip=T03_FV_tip(i);
STG(i).T1_FV_hub=T1_FV_hub(i);
STG(i).T1_FV_tip=T1_FV_tip(i);
STG(i).T2_FV_hub=T2_FV_hub(i);
STG(i).T2_FV_tip=T2_FV_tip(i);
STG(i).T3_FV_hub=T3_FV_hub(i);
STG(i).T3_FV_tip=T3_FV_tip(i);
STG(i).TONC_rtr_hub=TONC_rtr_hub(i);
STG(i).TONC_rtr_tip=TONC_rtr_tip(i);
STG(i).U1_FV_hub=U1_FV_hub(i);
STG(i).U1_FV_tip=U1_FV_tip(i);
STG(i).U2_FV_hub=U2_FV_hub(i);
STG(i).U2_FV_tip=U2_FV_tip(i);
STG(i).W1_FV_hub=W1_FV_hub(i);
STG(i).W1_FV_tip=W1_FV_tip(i);
STG(i).W_theta1_FV_hub=W_theta1_FV_hub(i);
STG(i).W_theta1_FV_tip=W_theta1_FV_tip(i);
STG(i).W2_FV_hub=W2_FV_hub(i);
STG(i).W2_FV_tip=W2_FV_tip(i);
STG(i).W_theta2_FV_hub=W_theta2_FV_hub(i);
STG(i).W_theta2_FV_tip=W_theta2_FV_tip(i);
STG(i).a1_FV_hub=a1_FV_hub(i);
STG(i).a1_FV_tip=a1_FV_tip(i);
STG(i).a2_FV_hub=a2_FV_hub(i);
STG(i).a2_FV_tip=a2_FV_tip(i);
STG(i).a3_FV_tip=a3_FV_tip(i);
STG(i).a3_FV_hub=a3_FV_hub(i);
STG(i).blade_angle_in_rtr_FV_hub=blade_angle_in_rtr_FV_hub(i);
STG(i).blade_angle_in_rtr_FV_tip=blade_angle_in_rtr_FV_tip(i);
STG(i).blade_angle_in_str_FV_hub=blade_angle_in_str_FV_hub(i);
STG(i).blade_angle_in_str_FV_tip=blade_angle_in_str_FV_tip(i);
STG(i).blade_angle_out_rtr_FV_hub=blade_angle_out_rtr_FV_hub(i);
STG(i).blade_angle_out_rtr_FV_tip=blade_angle_out_rtr_FV_tip(i);
STG(i).blade_angle_out_str_FV_hub=blade_angle_out_str_FV_hub(i);
STG(i).blade_angle_out_str_FV_tip=blade_angle_out_str_FV_tip(i);
STG(i).camber_angle_rtr_FV_hub=camber_angle_rtr_FV_hub(i);
STG(i).camber_angle_rtr_FV_tip=camber_angle_rtr_FV_tip(i);
STG(i).camber_angle_str_FV_hub=camber_angle_str_FV_hub(i);
STG(i).camber_angle_str_FV_tip=camber_angle_str_FV_tip(i);
STG(i).deviation_angle_rtr_FV_hub=deviation_angle_rtr_FV_hub(i);
STG(i).deviation_angle_rtr_FV_tip=deviation_angle_rtr_FV_tip(i);
STG(i).deviation_angle_str_FV_hub=deviation_angle_str_FV_hub(i);
STG(i).deviation_angle_str_FV_tip=deviation_angle_str_FV_tip(i);
STG(i).dH_rtr_FV_hub=dH_rtr_FV_hub(i);
STG(i).dH_rtr_FV_tip=dH_rtr_FV_tip(i);
STG(i).dH_str_FV_hub=dH_str_FV_hub(i);
STG(i).dH_str_FV_tip=dH_str_FV_tip(i);
STG(i).incidence_angle_rtr_FV_hub=incidence_angle_rtr_FV_hub(i);
STG(i).incidence_angle_rtr_FV_tip=incidence_angle_rtr_FV_tip(i);
STG(i).incidence_angle_str_FV_hub=incidence_angle_str_FV_hub(i);
STG(i).incidence_angle_str_FV_tip=incidence_angle_str_FV_tip(i);
STG(i).rho1_FV_hub=rho1_FV_hub(i);
STG(i).rho1_FV_tip=rho1_FV_tip(i);
STG(i).rho2_FV_hub=rho2_FV_hub(i);
STG(i).rho2_FV_tip=rho2_FV_tip(i);
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STG(i).rho3_FV_hub=rho3_FV_hub(i);
STG(i).rho3_FV_tip=rho3_FV_tip(i);
STG(i).stagger_angle_rtr_FV_hub=stagger_angle_rtr_FV_hub(i);
STG(i).stagger_angle_rtr_FV_tip=stagger_angle_rtr_FV_tip(i);
STG(i).stagger_angle_str_FV_hub=stagger_angle_str_FV_hub(i);
STG(i).stagger_angle_str_FV_tip=stagger_angle_str_FV_tip(i);
STG(i).turning_rtr_FV_hub = Beta1_FV_hub(i)-Beta2_FV_hub(i);
STG(i).turning_rtr_FV_tip = Beta1_FV_tip(i)-Beta2_FV_tip(i);
STG(i).turning_str_FV_hub = Alpha2_FV_hub(i)-Alpha3_FV_hub(i);
STG(i).turning_str_FV_tip = Alpha2_FV_tip(i)-Alpha3_FV_tip(i);

elseif proj_law == 'MFV' % General Whirl Distribution Values
STG(i).Alpha1_FREEV_hub=Alpha1_FREEV_hub(i);
STG(i).Alpha1_FREEV_tip=Alpha1_FREEV_tip(i);
STG(i).Alpha2=Alpha2(i);
STG(i).Alpha2_FREEV_hub=Alpha2_FREEV_hub(i);
STG(i).Alpha2_FREEV_tip=Alpha2_FREEV_tip(i);
STG(i).Alpha3=Alpha3(i);
STG(i).Alpha3_FREEV_hub=Alpha3_FREEV_hub(i);
STG(i).Alpha3_FREEV_tip=Alpha3_FREEV_tip(i);
STG(i).Beta1_FREEV_hub=Beta1_FREEV_hub(i);
STG(i).Beta1_FREEV_tip=Beta1_FREEV_tip(i);
STG(i).Beta2_FREEV_hub=Beta2_FREEV_hub(i);
STG(i).Beta2_FREEV_tip=Beta2_FREEV_tip(i);
STG(i).C1_FREEV_hub=C1_FREEV_hub(i);
STG(i).C1_FREEV_tip=C1_FREEV_tip(i);
STG(i).C2_FREEV_hub=C2_FREEV_hub(i);
STG(i).C2_FREEV_tip=C2_FREEV_tip(i);
STG(i).C3_FREEV_hub=C3_FREEV_hub(i);
STG(i).C3_FREEV_tip=C3_FREEV_tip(i);
STG(i).C_theta1_FREEV_hub=C_theta1_FREEV_hub(i);
STG(i).C_theta1_FREEV_tip=C_theta1_FREEV_tip(i);
STG(i).C_theta2_FREEV_hub=C_theta2_FREEV_hub(i);
STG(i).C_theta2_FREEV_tip=C_theta2_FREEV_tip(i);
STG(i).C_theta3_FREEV_hub=C_theta3_FREEV_hub(i);
STG(i).C_theta3_FREEV_tip=C_theta3_FREEV_tip(i);
STG(i).Cm1_FREEV_hub=Cm1_FREEV_hub(i);
STG(i).Cm1_FREEV_tip=Cm1_FREEV_tip(i);
STG(i).Cm2_FREEV_hub=Cm2_FREEV_hub(i);
STG(i).Cm2_FREEV_tip=Cm2_FREEV_tip(i);
STG(i).Cm3_FREEV_hub=Cm3_FREEV_hub(i);
STG(i).Cm3_FREEV_tip=Cm3_FREEV_tip(i);
STG(i).Cp1_FREEV_hub=Cp1_FREEV_hub(i);
STG(i).Cp1_FREEV_tip=Cp1_FREEV_tip(i);
STG(i).Cp2_FREEV_hub=Cp2_FREEV_hub(i);
STG(i).Cp2_FREEV_tip=Cp2_FREEV_tip(i);
STG(i).Cp3_FREEV_hub=Cp3_FREEV_hub(i);
STG(i).Cp3_FREEV_tip=Cp3_FREEV_tip(i);
STG(i).DF_lbl_rtr_FREEV_hub=DF_lbl_rtr_FREEV_hub(i);
STG(i).DF_lbl_rtr_FREEV_tip=DF_lbl_rtr_FREEV_tip(i);
STG(i).DF_lbl_str_FREEV_hub=DF_lbl_str_FREEV_hub(i);
STG(i).DF_lbl_str_FREEV_tip=DF_lbl_str_FREEV_tip(i);
STG(i).Deq_rtr_FREEV_hub=Deq_rtr_FREEV_hub(i);
STG(i).Deq_rtr_FREEV_tip=Deq_rtr_FREEV_tip(i);
STG(i).Deq_star_ks_rtr_FREEV_hub=Deq_star_ks_rtr_FREEV_hub(i);
STG(i).Deq_star_ks_rtr_FREEV_tip=Deq_star_ks_rtr_FREEV_tip(i);
STG(i).Deq_star_ks_str_FREEV_hub=Deq_star_ks_str_FREEV_hub(i);
STG(i).Deq_star_ks_str_FREEV_tip=Deq_star_ks_str_FREEV_tip(i);
STG(i).Deq_star_lbl_rtr_FREEV_hub=Deq_star_lbl_rtr_FREEV_hub(i);
STG(i).Deq_star_lbl_rtr_FREEV_tip=Deq_star_lbl_rtr_FREEV_tip(i);
STG(i).Deq_star_lbl_str_FREEV_hub=Deq_star_lbl_str_FREEV_hub(i);
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STG(i).Deq_star_lbl_str_FREEV_tip=Deq_star_lbl_str_FREEV_tip(i);
STG(i).Deq_str_FREEV_hub=Deq_str_FREEV_hub(i);
STG(i).Deq_str_FREEV_tip=Deq_str_FREEV_tip(i);
STG(i).H01_FREEV_hub=H01_FREEV_hub(i);
STG(i).H01_FREEV_tip=H01_FREEV_tip(i);
STG(i).H02_FREEV_hub=H02_FREEV_hub(i);
STG(i).H02_FREEV_tip=H02_FREEV_tip(i);
STG(i).H03_FREEV_hub=H03_FREEV_hub(i);
STG(i).H03_FREEV_tip=H03_FREEV_tip(i);
STG(i).H1_FREEV_hub=H1_FREEV_hub(i);
STG(i).H1_FREEV_tip=H1_FREEV_tip(i);
STG(i).H2_FREEV_hub=H2_FREEV_hub(i);
STG(i).H2_FREEV_tip=H2_FREEV_tip(i);
STG(i).H3_FREEV_hub=H3_FREEV_hub(i);
STG(i).H3_FREEV_tip=H3_FREEV_tip(i);
STG(i).MC2_FREEV_hub=MC2_FREEV_hub(i);
STG(i).MC2_FREEV_tip=MC2_FREEV_tip(i);
STG(i).MW1_FREEV_hub=MW1_FREEV_hub(i);
STG(i).MW1_FREEV_tip=MW1_FREEV_tip(i);
STG(i).Mcrit_Hearsey_rtr_FREEV_hub=Mcrit_Hearsey_rtr_FREEV_hub(i);
STG(i).Mcrit_Hearsey_rtr_FREEV_tip=Mcrit_Hearsey_rtr_FREEV_tip(i);
STG(i).Mcrit_Hearsey_str_FREEV_hub=Mcrit_Hearsey_str_FREEV_hub(i);
STG(i).Mcrit_Hearsey_str_FREEV_tip=Mcrit_Hearsey_str_FREEV_tip(i);
STG(i).P01_FREEV_hub=P01_FREEV_hub(i);
STG(i).P01_FREEV_tip=P01_FREEV_tip(i);
STG(i).P02_FREEV_hub=P02_FREEV_hub(i);
STG(i).P02_FREEV_tip=P02_FREEV_tip(i);
STG(i).P03_FREEV_hub=P03_FREEV_hub(i);
STG(i).P03_FREEV_tip=P03_FREEV_tip(i);
STG(i).P1_FREEV_hub=P1_FREEV_hub(i);
STG(i).P1_FREEV_tip=P1_FREEV_tip(i);
STG(i).P2_FREEV_hub=P2_FREEV_hub(i);
STG(i).P2_FREEV_tip=P2_FREEV_tip(i);
STG(i).P3_FREEV_hub=P3_FREEV_hub(i);
STG(i).P3_FREEV_tip=P3_FREEV_tip(i);
STG(i).REACT1_FREEV_hub=REACT1_FREEV_hub(i);
STG(i).REACT1_FREEV_tip= REACT1_FREEV_tip(i);
STG(i).SONC_rtr_FREEV_hub=SONC_rtr_FREEV_hub(i);
STG(i).SONC_rtr_FREEV_tip=SONC_rtr_FREEV_tip(i);
STG(i).SONC_str_FREEV_hub=SONC_str_FREEV_hub(i);
STG(i).SONC_str_FREEV_tip=SONC_str_FREEV_tip(i);
STG(i).T01_FREEV_hub=T01_FREEV_hub(i);
STG(i).T01_FREEV_tip=T01_FREEV_tip(i);
STG(i).T02_FREEV_hub=T02_FREEV_hub(i);
STG(i).T02_FREEV_tip=T02_FREEV_tip(i);
STG(i).T03_FREEV_hub=T03_FREEV_hub(i);
STG(i).T03_FREEV_tip=T03_FREEV_tip(i);
STG(i).T1_FREEV_hub=T1_FREEV_hub(i);
STG(i).T1_FREEV_tip=T1_FREEV_tip(i);
STG(i).T2_FREEV_hub=T2_FREEV_hub(i);
STG(i).T2_FREEV_tip=T2_FREEV_tip(i);
STG(i).T3_FREEV_hub=T3_FREEV_hub(i);
STG(i).T3_FREEV_tip=T3_FREEV_tip(i);
STG(i).TONC_rtr_hub=TONC_rtr_hub(i);
STG(i).TONC_rtr_tip=TONC_rtr_tip(i);
STG(i).U1_FREEV_hub=U1_FREEV_hub(i);
STG(i).U1_FREEV_tip=U1_FREEV_tip(i);
STG(i).U2_FREEV_hub=U2_FREEV_hub(i);
STG(i).U2_FREEV_tip=U2_FREEV_tip(i);
STG(i).W1_FREEV_hub=W1_FREEV_hub(i);
STG(i).W1_FREEV_tip=W1_FREEV_tip(i);
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    STG(i).W_theta1_FREEV_hub=W_theta1_FREEV_hub(i);
    STG(i).W_theta1_FREEV_tip=W_theta1_FREEV_tip(i);
    STG(i).W2_FREEV_hub=W2_FREEV_hub(i);
    STG(i).W2_FREEV_tip=W2_FREEV_tip(i);
    STG(i).W_theta2_FREEV_hub=W_theta2_FREEV_hub(i);
    STG(i).W_theta2_FREEV_tip=W_theta2_FREEV_tip(i);
    STG(i).a1_FREEV_hub=a1_FREEV_hub(i);
    STG(i).a1_FREEV_tip=a1_FREEV_tip(i);
    STG(i).a2_FREEV_hub=a2_FREEV_hub(i);
    STG(i).a2_FREEV_tip=a2_FREEV_tip(i);
    STG(i).a3_FREEV_tip=a3_FREEV_tip(i);
    STG(i).a3_FREEV_hub=a3_FREEV_hub(i);
    STG(i).blade_angle_in_rtr_FREEV_hub=blade_angle_in_rtr_FREEV_hub(i);
    STG(i).blade_angle_in_rtr_FREEV_tip=blade_angle_in_rtr_FREEV_tip(i);
    STG(i).blade_angle_in_str_FREEV_hub=blade_angle_in_str_FREEV_hub(i);
    STG(i).blade_angle_in_str_FREEV_tip=blade_angle_in_str_FREEV_tip(i);
    STG(i).blade_angle_out_rtr_FREEV_hub=blade_angle_out_rtr_FREEV_hub(i);
    STG(i).blade_angle_out_rtr_FREEV_tip=blade_angle_out_rtr_FREEV_tip(i);
    STG(i).blade_angle_out_str_FREEV_hub=blade_angle_out_str_FREEV_hub(i);
    STG(i).blade_angle_out_str_FREEV_tip=blade_angle_out_str_FREEV_tip(i);
    STG(i).camber_angle_rtr_FREEV_hub=camber_angle_rtr_FREEV_hub(i);
    STG(i).camber_angle_rtr_FREEV_tip=camber_angle_rtr_FREEV_tip(i);
    STG(i).camber_angle_str_FREEV_hub=camber_angle_str_FREEV_hub(i);
    STG(i).camber_angle_str_FREEV_tip=camber_angle_str_FREEV_tip(i);
    STG(i).deviation_angle_rtr_FREEV_hub=deviation_angle_rtr_FREEV_hub(i);
    STG(i).deviation_angle_rtr_FREEV_tip=deviation_angle_rtr_FREEV_tip(i);
    STG(i).deviation_angle_str_FREEV_hub=deviation_angle_str_FREEV_hub(i);
    STG(i).deviation_angle_str_FREEV_tip=deviation_angle_str_FREEV_tip(i);
    STG(i).dH_rtr_FREEV_hub=dH_rtr_FREEV_hub(i);
    STG(i).dH_rtr_FREEV_tip=dH_rtr_FREEV_tip(i);
    STG(i).dH_str_FREEV_hub=dH_str_FREEV_hub(i);
    STG(i).dH_str_FREEV_tip=dH_str_FREEV_tip(i);
    STG(i).incidence_angle_rtr_FREEV_hub=incidence_angle_rtr_FREEV_hub(i);
    STG(i).incidence_angle_rtr_FREEV_tip=incidence_angle_rtr_FREEV_tip(i);
    STG(i).incidence_angle_str_FREEV_hub=incidence_angle_str_FREEV_hub(i);
    STG(i).incidence_angle_str_FREEV_tip=incidence_angle_str_FREEV_tip(i);
    STG(i).rho1_FREEV_hub=rho1_FREEV_hub(i);
    STG(i).rho1_FREEV_tip=rho1_FREEV_tip(i);
    STG(i).rho2_FREEV_hub=rho2_FREEV_hub(i);
    STG(i).rho2_FREEV_tip=rho2_FREEV_tip(i);
    STG(i).rho3_FREEV_hub=rho3_FREEV_hub(i);
    STG(i).rho3_FREEV_tip=rho3_FREEV_tip(i);
    STG(i).stagger_angle_rtr_FREEV_hub=stagger_angle_rtr_FREEV_hub(i);
    STG(i).stagger_angle_rtr_FREEV_tip=stagger_angle_rtr_FREEV_tip(i);
    STG(i).stagger_angle_str_FREEV_hub=stagger_angle_str_FREEV_hub(i);
    STG(i).stagger_angle_str_FREEV_tip=stagger_angle_str_FREEV_tip(i);
    STG(i).turning_rtr_FREEV_hub = Beta1_FREEV_hub(i)-Beta2_FREEV_hub(i);
    STG(i).turning_rtr_FREEV_tip = Beta1_FREEV_tip(i)-Beta2_FREEV_tip(i);
    STG(i).turning_str_FREEV_hub = Alpha2_FREEV_hub(i)-Alpha3_FREEV_hub(i);
    STG(i).turning_str_FREEV_tip = Alpha2_FREEV_tip(i)-Alpha3_FREEV_tip(i);

     end


end
clc
```

C, Results

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                              ------------------------------------------------------------
                              |                        LUAX-C                            |
                              |                      Version 2.0                         |
                              |      Niclas Falck & Magnus Genrup & Daniele Perrotti     |
                              |                         2013                             |
                              ------------------------------------------------------------
Name: Comp
______________________________________________________________________________________________________________
05-Apr-2013 11:15:16

************************************************************ FORCED VORTEX LAW ******************************************************************

Type:                  Constant Exit Hub to Tip Ratio
Pressure ratio:        20
Number of stages:      16
Inlet massflow:        122 kg/s
Rotational speed:      6600 rpm
Ambient pressure:      1 bar
Ambient temperature:   15 C


===== Compressor Performance =====
=====================================================================================================================================

Polytropic efficiency:   92.69 %
Isentropic efficiency:   90.91 %
Temperature rise:        422.5 K
Inlet Mach @ tip:        1.08
massflow @ 3000:         590.5 kg/s
specific massflow:       231.4 kg/(s m^2)
Compressor cost:         703000 €
Compressor power:        53.31 MW


===== Koch Surgelimit =====
Stage          1       2       3       4       5       6       7       8       9       10      11      12      13      14      15      16
Ch           0.400   0.427   0.425   0.422   0.421   0.425   0.430   0.435   0.439   0.442   0.440   0.438   0.436   0.433   0.429   0.428
Ch_max       0.433   0.437   0.438   0.438   0.440   0.444   0.448   0.452   0.457   0.461   0.462   0.464   0.466   0.467   0.469   0.472
Ch/Ch_max    0.925   0.977   0.970   0.963   0.957   0.959   0.959   0.961   0.961   0.960   0.953   0.945   0.936   0.926   0.915   0.905


===== STAGE 1 =====
====================================================================================================================================

PR      REACT    Flow   PSI     PHI     dT0      dS       ------Efficiencies------    --------Surge (Koch)------
                                                          Poly    Isen    acc.Poly    Ch      Ch_max   Ch/Ch_max
1.444   0.550     122   0.411   0.646   34.556   8.545    0.925   0.921   0.925       0.400   0.433    0.925


point   ------radius-------     ------------------------------Velocities--------------------------------------
                                **********U***********   *********Cm***********   ***********C**********
          hub     mid     tip     hub     mid     tip     hub     mid     tip     hub     mid     tip
    1   0.274   0.421   0.528   189.7   290.7   364.7   189.0   189.0   189.0   195.6   195.6   195.6
    2   0.301   0.421   0.513   208.0   290.7   354.6   212.9   186.8   166.4   263.6   252.7   245.6
    3   0.312   0.421   0.507   N/A     N/A     N/A     190.5   184.6   178.5   194.0   199.3   188.2
```

point	Velocities: W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles: Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	251.4	305.5	351.4	33.0	50.6	63.5	15.00	15.00	15.00	38.55	51.79	59.00
2	219.3	222.2	240.7	155.4	170.2	180.6	36.12	42.35	47.36	13.87	32.82	46.28
3	N/A	N/A	N/A	36.7	75.2	59.6	10.90	22.17	18.45	N/A	N/A	N/A

point	Pressure: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	1.01	1.01	1.01	0.80	0.80	0.80	14.9	14.9	14.9	-4.2	-4.2	-4.2
2	1.35	1.48	1.56	0.90	1.03	1.12	41.5	49.4	54.8	6.9	17.7	24.8
3	1.34	1.46	1.55	1.08	1.17	1.28	41.5	49.4	54.8	22.8	29.7	37.2

point	Enthalpy: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	14.9	14.9	14.9	-4.2	-4.2	-4.2
2	41.7	49.7	55.1	7.0	17.8	24.9
3	41.7	49.7	55.1	22.9	29.8	37.4

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	53.27	1004.5	1004.5	1004.5	1.400	1.032	1.032	1.032	328.932	328.932	328.932
2	59.31	1004.9	1005.3	1005.7	1.400	1.118	1.229	1.305	335.641	341.983	346.120
3	61.81	1005.6	1005.9	1006.3	1.400	1.272	1.348	1.433	344.960	348.923	353.186

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
rotor	0.873	0.727	0.685	0.194	0.435	0.545	1.262	1.632	1.752	1.446	1.840	2.048	1.446	1.840	2.048	0.010	0.025
stator	0.736	0.789	0.766	0.409	0.383	0.509	1.586	1.519	1.719	1.743	1.684	1.873	1.743	1.684	1.873	0.007	0.021

	Mach: relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.764	0.929	1.068	0.869	0.894	0.924	2.500	0.555	0.829	1.004	0.090	0.060	0.030	0.553
stator	0.785	0.739	0.710	0.895	0.893	0.887	3.500	0.663	0.913	1.103	0.060	0.060	0.060	0.601

	Nr.blades	Blade angles: inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	35.00	36.41	52.72	59.88	8.56	25.29	39.77	2.14	-0.92	-0.88
stator	50.00	36.11	45.56	57.39	4.56	13.53	0.37	0.01	-3.21	-10.04

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===== STAGE 2 =====
==================================================================================================================================

PR       REACT    Flow   PSI     PHI     dT0      dS      ------Efficiencies------    --------Surge (Koch)------
                                                          Poly     Isen    acc.Poly   Ch       Ch_max    Ch/Ch_max
1.376    0.550     122   0.401   0.637   33.043   6.610   0.933    0.930   0.929      0.427    0.437     0.977

point    ------radius-------     ------------------------------Velocities--------------------------------------
                                  **********U***********    *********Cm***********     ***********C**********
           hub     mid     tip     hub      mid      tip      hub      mid      tip      hub      mid      tip
    1    0.307   0.417   0.503   212.0    288.1    347.9    198.1    184.6    170.0    201.8    199.3    179.2
    2    0.318   0.417   0.496   219.9    288.1    343.0    217.2    182.4    150.6    277.3    264.0    253.7
    3    0.329   0.417   0.489   N/A      N/A      N/A      191.3    180.3    168.6    199.9    195.7    189.4

point     ------------------------Velocities------------------------   --------------------Angles-----------------------------
           ***********W***********     **********C_theta************   ************Alpha*******     *************Beta************
          hub       mid       tip       hub       m         tip        hub       mid       tip       hub       mid       tip
    1     252.6     281.8     308.2     55.3      75.2      90.8       10.90     22.17     18.45     38.33     49.07     56.53
    2     222.4     206.7     204.8     172.4     190.9     204.1      38.44     46.29     53.58     12.34     28.06     42.67
    3     N/A       N/A       N/A       57.9      75.9      86.2       16.85     22.84     27.09     N/A       N/A       N/A

point    --------------------Pressure-------------------    -----------------Temperatures------------------
         ********Total********    ********Static********    ********Total********    *********Static*********
          hub     mid     tip      hub     mid     tip      hub     mid      tip      hub        mid     tip
    1     1.34    1.46    1.55     1.17    1.17    1.22     41.5    49.4     54.8     29.2       29.7    33.5
    2     1.91    2.03    2.18     1.27    1.42    1.58     76.2    82.4     90.0     38.0       47.9    58.1
    3     1.89    2.01    2.17     1.54    1.66    1.82     76.2    82.4     90.0     56.4       63.5    72.2

point    -------------------------Enthalpy-------------------------
         ************Total************     *********Static********
          hub        mid        tip         hub      mid      tip
    1     41.7       49.7       55.1        29.3     29.8     33.6
    2     76.7       83.0       90.6        38.2     48.2     58.4
    3     76.7       83.0       90.6        56.7     63.9     72.7

point        Entropy     -----------Cp-----------        ----Kappa----     --------rho--------        ------------a-------------
                         hub        mid        tip            mid          hub     mid     tip         hub          mid          tip
    1         61.81        1005.9     1005.9     1006.1       1.400        1.342   1.348   1.390       348.643      348.923      351.086
    2         66.00        1006.4     1007.0     1007.7       1.399        1.422   1.537   1.663       353.667      359.185      364.806
    3         68.42        1007.6     1008.1     1008.8       1.398        1.627   1.717   1.831       363.858      367.727      372.422

          ---deHaller---      --------DF---------     --------Deq--------     --------------------Deq*--------------------   Loss Coefficients
                                                                              ******Lieblein*****     *****Koch/Smith*****   Endwall  Profile
          hub   mid   tip      hub     mid     tip     hub     mid     tip     hub     mid     tip     hub     mid     tip
rotor   0.880 0.734 0.665     0.242   0.430   0.519   1.335   1.620   1.710   1.495   1.810   1.988   1.495   1.810   1.988    0.011    0.023
stator  0.721 0.741 0.747     0.395   0.423   0.462   1.572   1.605   1.662   1.755   1.780   1.831   1.755   1.780   1.831    0.007    0.021
```

	Mach relative hub	Mach relative mid	Mach relative tip	Mach critical hub	Mach critical mid	Mach critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.725	0.808	0.878	0.868	0.894	0.924	2.400	0.585	0.795	0.936	0.090	0.060	0.030	0.625
stator	0.784	0.735	0.695	0.896	0.894	0.890	3.330	0.580	0.755	0.883	0.060	0.060	0.060	0.657

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	43.00	37.24	51.21	59.66	6.33	20.01	35.36	1.09	-2.14	-3.13
stator	69.00	37.04	48.85	61.46	12.17	14.59	13.52	1.39	-2.56	-7.87

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	6.02	8.05	7.31	30.91	31.20	24.30	22.88	33.47	44.38	25.99	21.01	13.86
stator	4.68	8.25	13.57	24.87	34.26	47.94	26.00	29.16	29.61	21.59	23.45	26.50

===== STAGE 3 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Isen	acc.Poly	Surge (Koch) Ch	Ch_max	Ch/Ch_max
1.322	0.550	122	0.391	0.628	31.550	5.832	0.932	0.929	0.930	0.425	0.438	0.970

point	radius hub	radius mid	radius tip	Velocities U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.324	0.413	0.486	223.9	285.5	336.0	192.2	180.3	167.6	200.9	195.7	188.2
2	0.331	0.413	0.481	229.0	285.5	332.6	207.8	178.2	150.4	269.7	258.8	249.6
3	0.339	0.413	0.476	N/A	N/A	N/A	186.1	176.2	165.6	195.8	192.1	186.4

point	Velocities W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	252.9	276.5	298.2	59.6	75.9	89.4	16.85	22.84	27.09	40.53	49.29	55.81
2	215.5	203.3	201.0	171.9	187.7	199.2	39.60	46.48	52.94	15.34	28.76	41.57
3	N/A	N/A	N/A	60.8	76.6	85.5	18.09	23.52	27.30	N/A	N/A	N/A

point	Pressure Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	1.89	2.01	2.17	1.64	1.66	1.68	76.2	82.4	90.0	62.5	63.5	64.9
2	2.54	2.68	2.79	1.79	1.96	2.09	108.3	114.0	118.6	72.3	80.9	87.8
3	2.52	2.66	2.77	2.11	2.24	2.37	108.3	114.0	118.6	89.3	95.8	101.4

point	Enthalpy Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	76.7	83.0	90.6	62.8	63.9	65.3
2	109.1	114.9	119.5	72.7	81.4	88.4
3	109.1	114.9	119.5	89.9	96.5	102.2

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	68.42	1008.0	1008.1	1008.2	1.398	1.704	1.717	1.735	367.173	367.727	368.493
2	72.09	1008.8	1009.5	1010.1	1.398	1.808	1.924	2.020	372.452	377.004	380.618
3	74.26	1010.3	1010.9	1011.5	1.397	2.026	2.118	2.201	381.417	384.745	387.639

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
rotor	0.852	0.735	0.674	0.279	0.428	0.506	1.394	1.616	1.681	1.550	1.803	1.952	1.550	1.803	1.952	0.011	0.023
stator	0.726	0.742	0.747	0.399	0.422	0.458	1.576	1.603	1.655	1.750	1.776	1.824	1.750	1.776	1.824	0.007	0.021

	Mach relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.689	0.752	0.809	0.867	0.894	0.924	2.300	0.632	0.809	0.933	0.090	0.060	0.030	0.677
stator	0.724	0.687	0.656	0.896	0.894	0.891	3.170	0.619	0.767	0.885	0.060	0.060	0.060	0.700

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	48.00	40.66	52.23	59.91	8.63	20.46	33.78	-0.13	-2.94	-4.10
stator	75.00	39.45	49.73	60.86	12.79	15.07	14.11	0.15	-3.25	-7.92

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	6.71	8.30	7.78	32.03	31.77	26.13	24.51	33.40	42.74	25.19	20.53	14.24
stator	5.30	8.45	13.19	26.66	34.66	46.74	26.27	29.15	29.57	21.51	22.96	25.64

===== STAGE 4 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Isen	acc.Poly	Surge (Koch) Ch	Ch_max	Ch/Ch_max
1.279	0.550	122	0.381	0.619	30.082	5.220	0.931	0.929	0.930	0.422	0.438	0.963

point	radius hub	radius mid	radius tip	Velocities U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.334	0.409	0.473	230.9	282.9	326.7	187.0	176.2	164.6	196.7	192.1	185.3
2	0.339	0.409	0.469	234.2	282.9	324.3	200.2	174.1	149.1	263.1	253.7	245.3
3	0.344	0.409	0.465	N/A	N/A	N/A	181.4	172.1	162.3	192.0	188.7	183.3

point	Velocities: W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles: Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	251.6	271.2	289.6	62.5	76.6	88.5	18.09	23.51	27.30	41.99	49.50	55.35
2	210.1	200.0	197.6	170.6	184.5	194.7	40.44	46.67	52.56	17.63	29.46	40.99
3	N/A	N/A	N/A	63.0	77.3	85.1	19.15	24.21	27.67	N/A	N/A	N/A

point	Pressure: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	2.52	2.66	2.77	2.23	2.24	2.27	108.3	114.0	118.6	94.9	95.8	97.0
2	3.29	3.43	3.54	2.42	2.59	2.74	139.3	144.1	148.0	105.1	112.4	118.4
3	3.27	3.40	3.52	2.78	2.92	3.05	139.3	144.1	148.0	121.1	126.6	131.5

point	Enthalpy: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	109.1	114.9	119.5	95.6	96.5	97.7
2	140.5	145.4	149.5	105.9	113.2	119.4
3	140.5	145.4	149.5	122.1	127.6	132.7

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	74.26	1010.8	1010.9	1011.0	1.397	2.105	2.118	2.136	384.292	384.745	385.399
2	77.51	1011.9	1012.7	1013.4	1.396	2.231	2.340	2.434	389.523	393.169	396.185
3	79.48	1013.7	1014.3	1015.0	1.395	2.459	2.546	2.627	397.520	400.212	402.635

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
rotor	0.835	0.737	0.682	0.301	0.426	0.495	1.431	1.613	1.658	1.585	1.798	1.923	1.585	1.798	1.923	0.012	0.022
stator	0.730	0.744	0.747	0.401	0.421	0.453	1.576	1.600	1.648	1.747	1.772	1.818	1.747	1.772	1.818	0.007	0.021

	Mach: relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.655	0.705	0.751	0.867	0.894	0.924	2.200	0.665	0.823	0.931	0.090	0.060	0.030	0.714
stator	0.675	0.645	0.619	0.896	0.894	0.891	3.000	0.649	0.779	0.887	0.060	0.060	0.060	0.731

	Nr.blades	Blade angles: inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	52.00	43.05	53.14	60.20	10.45	20.94	32.92	-1.06	-3.64	-4.85
stator	79.00	41.25	50.53	60.63	13.39	15.57	14.73	-0.82	-3.86	-8.07

	Blade angles: deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	7.17	8.52	8.07	32.60	32.21	27.28	25.69	33.40	41.71	24.37	20.04	14.36
stator	5.76	8.64	12.94	27.86	34.96	45.89	26.50	29.18	29.61	21.28	22.46	24.88

===== STAGE 5 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies: Poly	Isen	acc.Poly	Surge (Koch): Ch	Ch_max	Ch/Ch_max
1.245	0.550	122	0.371	0.610	28.643	4.722	0.930	0.928	0.930	0.421	0.440	0.957

point	radius: hub	mid	tip	Velocities: U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.340	0.406	0.462	234.9	280.3	319.3	182.1	172.1	161.4	192.8	188.7	182.3
2	0.343	0.406	0.459	237.2	280.3	317.6	193.8	170.1	147.1	257.0	248.7	240.9
3	0.347	0.406	0.456	N/A	N/A	N/A	176.9	168.1	158.8	188.4	184.7	180.1

point	Velocities: W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles: Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	249.2	266.1	282.0	64.8	77.3	88.1	19.15	24.20	27.67	43.04	49.71	55.08
2	205.5	196.7	194.3	168.8	181.4	190.7	41.06	46.85	52.35	19.45	30.17	40.77
3	N/A	N/A	N/A	64.7	76.5	85.0	20.09	24.48	28.15	N/A	N/A	N/A

point	Pressure: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	3.27	3.40	3.52	2.90	2.92	2.95	139.3	144.1	148.0	125.8	126.6	127.7
2	4.12	4.26	4.38	3.15	3.32	3.47	168.6	172.7	176.2	136.1	142.4	147.7
3	4.10	4.24	4.35	3.55	3.70	3.83	168.6	172.7	176.2	151.1	156.0	160.3

point	Enthalpy: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	140.5	145.4	149.5	126.8	127.6	128.8
2	170.4	174.6	178.2	137.3	143.7	149.2
3	170.4	174.6	178.2	152.6	157.6	161.9

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	79.48	1014.2	1014.3	1014.5	1.395	2.534	2.546	2.565	399.829	400.212	400.786
2	82.41	1015.6	1016.4	1017.1	1.394	2.676	2.781	2.873	404.870	407.887	410.460
3	84.20	1017.6	1018.3	1019.0	1.393	2.914	3.000	3.077	412.073	414.368	416.389

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
rotor	0.825	0.739	0.689	0.316	0.425	0.487	1.458	1.609	1.641	1.611	1.793	1.904	1.611	1.793	1.904	0.012	0.022
stator	0.733	0.743	0.748	0.398	0.422	0.445	1.571	1.602	1.635	1.740	1.773	1.805	1.740	1.773	1.805	0.008	0.020

	Mach relative			Mach critical			H/C	S/C			T/C			H/T
	hub	mid	tip	hub	mid	tip		hub	mid	tip	hub	mid	tip	
rotor	0.623	0.665	0.704	0.867	0.894	0.924	2.100	0.700	0.839	0.945	0.090	0.060	0.030	0.741
stator	0.635	0.610	0.587	0.896	0.894	0.891	2.830	0.657	0.780	0.872	0.060	0.060	0.060	0.754

	Nr.blades	Blade angles inlet			Blade angles outlet			Blade angles incidence		
		hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	54.00	45.02	53.98	60.69	11.81	21.43	32.33	-1.98	-4.27	-5.61
stator	83.00	42.45	51.17	60.26	14.16	15.71	15.77	-1.39	-4.32	-7.91

	Blade angles deviation			Blade angles camber			Blade angles stagger			Blade angles turning		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	7.64	8.74	8.45	33.21	32.55	28.36	26.44	33.43	40.90	23.59	19.54	14.31
stator	5.94	8.77	12.38	28.29	35.46	44.49	26.91	29.12	30.11	20.96	22.37	24.20

===== STAGE 6 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Efficiencies Isen	Efficiencies acc.Poly	Surge (Koch) Ch	Surge (Koch) Ch_max	Surge (Koch) Ch/Ch_max
1.224	0.550	122	0.371	0.602	27.990	4.349	0.930	0.928	0.930	0.425	0.444	0.959

point	radius			Velocities U			Velocities Cm			Velocities C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.343	0.402	0.453	237.1	277.7	313.1	177.3	168.1	158.4	188.8	184.7	179.7
2	0.347	0.402	0.450	240.0	277.7	310.8	187.2	166.2	145.6	251.9	244.7	237.6
3	0.351	0.402	0.447	N/A	N/A	N/A	172.2	164.2	155.9	184.1	180.8	176.7

point	Velocities W			Velocities C_theta			Angles Alpha			Angles Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	246.9	262.2	276.6	65.3	76.5	86.3	20.09	24.47	28.15	44.09	50.12	55.07
2	200.4	192.9	190.6	168.5	179.7	187.8	41.99	47.23	52.21	20.90	30.54	40.20
3	N/A	N/A	N/A	65.2	75.7	83.2	20.75	24.76	28.09	N/A	N/A	N/A

point	Pressure Total			Pressure Static			Temperatures Total			Temperatures Static		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	4.10	4.24	4.35	3.68	3.70	3.73	168.6	172.7	176.2	155.2	156.0	156.9
2	5.07	5.21	5.32	3.98	4.15	4.30	197.2	200.7	203.5	166.1	171.4	175.9
3	5.04	5.18	5.29	4.44	4.59	4.71	197.2	200.7	203.5	180.6	184.8	188.3

point	Enthalpy Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	170.4	174.6	178.2	156.8	157.6	158.5
2	199.6	203.3	206.1	167.9	173.3	177.9
3	199.6	203.3	206.1	182.7	186.9	190.5

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	84.20	1018.2	1018.3	1018.5	1.393	2.987	3.000	3.016	414.015	414.368	414.794
2	86.89	1019.8	1020.7	1021.4	1.392	3.154	3.252	3.337	419.106	421.573	423.628
3	88.55	1022.2	1022.8	1023.4	1.390	3.406	3.487	3.556	425.766	427.655	429.242

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Loss Coefficients Profile
rotor	0.812	0.736	0.689	0.329	0.428	0.486	1.481	1.615	1.639	1.636	1.799	1.898	1.636	1.799	1.898	0.013	0.022
stator	0.731	0.739	0.744	0.405	0.425	0.447	1.582	1.609	1.640	1.751	1.780	1.810	1.751	1.780	1.810	0.008	0.020

	Mach relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.596	0.633	0.667	0.867	0.894	0.924	2.000	0.704	0.831	0.921	0.090	0.060	0.030	0.765
stator	0.601	0.580	0.561	0.896	0.894	0.892	2.670	0.668	0.772	0.859	0.060	0.060	0.060	0.778

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	58.00	46.48	54.78	61.15	13.11	21.68	31.55	-2.39	-4.67	-6.08
stator	88.00	44.00	51.87	60.17	14.43	15.90	15.90	-2.02	-4.64	-7.96

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	7.79	8.86	8.65	33.37	33.10	29.60	27.41	33.57	40.27	23.19	19.57	14.87
stator	6.32	8.86	12.18	29.58	35.98	44.27	27.20	29.25	30.08	21.24	22.47	24.13

===== STAGE 7 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Isen	acc.Poly	Surge (Koch) Ch	Ch_max	Ch/Ch_max
1.205	0.550	122	0.371	0.594	27.337	4.040	0.930	0.928	0.930	0.430	0.448	0.959

point	radius hub	radius mid	radius tip	Velocities U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.346	0.398	0.444	239.3	275.1	306.7	172.5	164.2	155.5	184.5	180.8	176.3
2	0.350	0.398	0.441	241.6	275.1	304.9	181.3	162.3	143.7	247.1	240.8	234.3
3	0.352	0.398	0.439	N/A	N/A	N/A	167.7	160.4	152.9	180.0	177.1	173.3

point	Velocities: W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles: Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	244.6	258.3	271.3	65.9	75.7	84.4	20.75	24.75	28.09	45.15	50.52	55.03
2	195.7	189.2	187.1	167.9	177.9	185.1	42.80	47.62	52.18	22.13	30.92	39.82
3	N/A	N/A	N/A	65.5	74.9	81.6	21.33	25.04	28.09	N/A	N/A	N/A

point	Pressure: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	5.04	5.18	5.29	4.56	4.59	4.61	197.2	200.7	203.5	184.1	184.8	185.5
2	6.14	6.28	6.39	4.93	5.10	5.26	224.9	228.1	230.5	195.2	199.8	203.8
3	6.11	6.25	6.36	5.44	5.59	5.72	224.9	228.1	230.5	209.1	212.8	216.0

point	Enthalpy: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	199.6	203.3	206.1	186.2	186.9	187.7
2	228.1	231.4	233.9	197.6	202.4	206.5
3	228.1	231.4	233.9	211.9	215.7	218.9

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	88.55	1022.7	1022.8	1023.0	1.390	3.474	3.487	3.502	427.361	427.655	428.017
2	91.05	1024.6	1025.4	1026.2	1.389	3.662	3.757	3.839	432.345	434.433	436.205
3	92.59	1027.1	1027.8	1028.4	1.388	3.928	4.006	4.073	438.539	440.154	441.522

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
rotor	0.800	0.732	0.690	0.345	0.431	0.485	1.510	1.622	1.638	1.665	1.805	1.895	1.665	1.805	1.895	0.014	0.022
stator	0.728	0.735	0.739	0.410	0.428	0.448	1.592	1.616	1.645	1.760	1.787	1.814	1.760	1.787	1.814	0.009	0.020

	Mach: relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.572	0.604	0.634	0.867	0.894	0.924	1.900	0.720	0.824	0.916	0.090	0.060	0.030	0.786
stator	0.572	0.554	0.537	0.896	0.894	0.892	2.500	0.672	0.764	0.843	0.060	0.060	0.060	0.797

	Nr.blades	Blade angles: inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	61.00	48.18	55.54	61.64	13.94	21.95	30.87	-3.02	-5.02	-6.61
stator	92.00	45.30	52.54	60.13	14.73	16.10	16.13	-2.50	-4.92	-7.95

	Blade angles: deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	8.19	8.96	8.95	34.23	33.59	30.77	28.04	33.73	39.64	23.02	19.61	15.21
stator	6.60	8.94	11.95	30.57	36.44	43.99	27.52	29.40	30.18	21.48	22.58	24.09

===== STAGE 8 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies			Surge (Koch)		
							Poly	Isen	acc.Poly	Ch	Ch_max	Ch/Ch_max
1.189	0.550	122	0.371	0.585	26.686	3.781	0.929	0.928	0.930	0.435	0.452	0.961

point	radius			Velocities U			Velocities Cm			Velocities C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.348	0.394	0.436	240.5	272.5	301.1	168.0	160.4	152.5	180.3	177.1	172.9
2	0.351	0.394	0.433	242.4	272.5	299.6	175.9	158.6	141.5	242.6	237.0	231.0
3	0.353	0.394	0.432	N/A	N/A	N/A	163.4	156.7	149.8	176.0	173.4	169.9

point	Velocities W			Velocities C_theta			Angles Alpha			Angles Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	242.1	254.5	266.3	66.1	74.9	82.8	21.33	25.03	28.09	46.07	50.92	55.06
2	191.3	185.6	183.6	167.1	176.1	182.6	43.53	48.00	52.23	23.19	31.29	39.58
3	N/A	N/A	N/A	65.5	74.1	80.1	21.84	25.32	28.14	N/A	N/A	N/A

point	Pressure Total			Pressure Static			Temperatures Total			Temperatures Static		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	6.11	6.25	6.36	5.57	5.59	5.62	224.9	228.1	230.5	212.3	212.8	213.5
2	7.32	7.47	7.58	5.99	6.17	6.33	251.9	254.7	257.0	223.4	227.6	231.2
3	7.29	7.43	7.54	6.56	6.72	6.85	251.9	254.7	257.0	236.9	240.2	243.0

point	Enthalpy Total			Enthalpy Static		
	hub	mid	tip	hub	mid	tip
1	228.1	231.4	233.9	215.1	215.7	216.4
2	256.0	258.9	261.2	226.6	230.9	234.6
3	256.0	258.9	261.2	240.5	243.9	246.8

point	Entropy	Cp			Kappa	rho			a		
		hub	mid	tip	mid	hub	mid	tip	hub	mid	tip
1	92.59	1027.7	1027.8	1027.9	1.388	3.994	4.006	4.021	439.905	440.154	440.465
2	94.92	1029.8	1030.6	1031.3	1.386	4.201	4.293	4.373	444.752	446.545	448.089
3	96.37	1032.5	1033.1	1033.7	1.385	4.481	4.556	4.622	450.539	451.938	453.130

	deHaller			DF			Deq			Deq* Lieblein			Deq* Koch/Smith			Loss Coefficients	
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip	Endwall	Profile
rotor	0.790	0.729	0.689	0.354	0.433	0.481	1.528	1.629	1.634	1.685	1.812	1.886	1.685	1.812	1.886	0.014	0.021
stator	0.726	0.732	0.735	0.414	0.431	0.449	1.600	1.624	1.649	1.768	1.794	1.818	1.768	1.794	1.818	0.009	0.020

	Mach: relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.550	0.578	0.605	0.867	0.894	0.924	1.800	0.714	0.818	0.888	0.090	0.060	0.030	0.804
stator	0.545	0.531	0.516	0.896	0.894	0.892	2.330	0.672	0.757	0.826	0.060	0.060	0.060	0.813

	Nr.blades	Blade angles: inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	65.00	49.33	56.26	61.84	14.93	22.23	30.72	-3.25	-5.33	-6.78
stator	95.00	46.40	53.17	60.14	15.04	16.31	16.42	-2.87	-5.18	-7.92

	Blade angles: deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	8.26	9.06	8.86	34.39	34.02	31.12	28.88	33.91	39.50	22.88	19.63	15.48
stator	6.80	9.01	11.72	31.36	36.86	43.72	27.85	29.57	30.36	21.68	22.68	24.09

===== STAGE 9 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies: Poly	Isen	acc.Poly	Surge (Koch): Ch	Ch_max	Ch/Ch_max
1.176	0.550	122	0.371	0.577	26.040	3.563	0.929	0.927	0.930	0.439	0.457	0.961

point	radius hub	radius mid	radius tip	Velocities: U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.349	0.390	0.428	241.0	269.9	296.0	163.7	156.7	149.5	176.3	173.4	169.5
2	0.351	0.390	0.426	242.5	269.9	294.7	170.9	154.9	139.1	238.3	233.2	227.7
3	0.353	0.390	0.425	N/A	N/A	N/A	159.3	153.1	146.7	172.2	169.8	166.5

point	Velocities: W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles: Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	239.5	250.8	261.6	66.2	74.1	81.3	21.84	25.30	28.14	46.89	51.32	55.16
2	187.2	182.0	180.2	166.1	174.3	180.2	44.18	48.38	52.33	24.12	31.67	39.45
3	N/A	N/A	N/A	65.4	73.3	78.8	22.32	25.60	28.24	N/A	N/A	N/A

point	Pressure: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures: Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	7.29	7.43	7.54	6.70	6.72	6.75	251.9	254.7	257.0	239.7	240.2	240.9
2	8.63	8.77	8.89	7.18	7.37	7.53	278.2	280.8	282.8	250.9	254.6	257.9
3	8.59	8.73	8.85	7.81	7.97	8.11	278.2	280.8	282.8	263.9	266.9	269.5

point	Enthalpy Total hub	mid	tip	Enthalpy Static hub	mid	tip
1	256.0	258.9	261.2	243.4	243.9	244.6
2	283.3	286.0	288.1	254.9	258.8	262.2
3	283.3	286.0	288.1	268.5	271.6	274.2

point	Entropy	Cp hub	mid	tip	Kappa mid	rho hub	mid	tip	a hub	mid	tip
1	96.37	1033.0	1033.1	1033.2	1.385	4.545	4.556	4.571	451.725	451.938	452.209
2	98.57	1035.3	1036.1	1036.7	1.384	4.770	4.859	4.938	456.416	457.976	459.335
3	99.93	1038.0	1038.7	1039.2	1.382	5.062	5.136	5.200	461.845	463.072	464.120

	deHaller hub	mid	tip	DF hub	mid	tip	Deq hub	mid	tip	Deq* Lieblein hub	mid	tip	Deq* Koch/Smith hub	mid	tip	Loss Coefficients Endwall	Profile
rotor	0.782	0.726	0.689	0.365	0.436	0.481	1.548	1.636	1.635	1.705	1.818	1.886	1.705	1.818	1.886	0.015	0.021
stator	0.723	0.728	0.731	0.418	0.435	0.450	1.608	1.631	1.654	1.777	1.802	1.823	1.777	1.802	1.823	0.010	0.020

	Mach relative hub	mid	tip	Mach critical hub	mid	tip	H/C	S/C hub	mid	tip	T/C hub	mid	tip	H/T
rotor	0.530	0.555	0.578	0.867	0.894	0.924	1.700	0.720	0.811	0.879	0.090	0.060	0.030	0.819
stator	0.522	0.509	0.496	0.896	0.894	0.893	2.170	0.670	0.750	0.811	0.060	0.060	0.060	0.827

	Nr.blades	Blade angles inlet hub	mid	tip	outlet hub	mid	tip	incidence hub	mid	tip
rotor	67.00	50.56	56.94	62.29	15.62	22.52	30.45	-3.67	-5.62	-7.13
stator	97.00	47.38	53.78	60.25	15.35	16.53	16.69	-3.20	-5.40	-7.92

	Blade angles deviation hub	mid	tip	camber hub	mid	tip	stagger hub	mid	tip	turning hub	mid	tip
rotor	8.50	9.14	9.01	34.94	34.41	31.84	29.42	34.11	39.24	22.77	19.66	15.71
stator	6.97	9.07	11.54	32.04	37.25	43.56	28.16	29.75	30.55	21.86	22.78	24.10

===== STAGE 10 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Isen	acc.Poly	Surge (Koch) Ch	Ch_max	Ch/Ch_max
1.163	0.550	122	0.371	0.570	25.403	3.385	0.928	0.926	0.930	0.442	0.461	0.960

point	radius			Velocities U			Velocities Cm			Velocities C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.349	0.387	0.421	240.9	267.3	291.3	159.6	153.1	146.4	172.5	169.8	166.1
2	0.350	0.387	0.420	242.2	267.3	290.2	166.2	151.3	136.6	234.1	229.5	224.3
3	0.352	0.387	0.419	N/A	N/A	N/A	155.3	149.6	143.6	168.5	166.6	163.2

point	Velocities W			Velocities C_theta			Angles Alpha			Angles Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	236.7	247.1	257.1	66.1	73.3	79.9	22.32	25.58	28.24	47.62	51.72	55.30
2	183.3	178.5	176.8	164.9	172.6	177.9	44.79	48.75	52.49	24.94	32.04	39.41
3	N/A	N/A	N/A	65.2	73.4	77.5	22.76	26.17	28.37	N/A	N/A	N/A

point	Pressure Total			Pressure Static			Temperatures Total			Temperatures Static		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	8.59	8.73	8.85	7.94	7.97	8.00	278.2	280.8	282.8	266.5	266.9	267.5
2	10.06	10.21	10.32	8.49	8.68	8.85	303.8	306.2	308.0	277.6	281.0	284.0
3	10.01	10.16	10.28	9.18	9.34	9.48	303.8	306.2	308.0	290.3	292.9	295.3

point	Enthalpy Total			Enthalpy Static		
	hub	mid	tip	hub	mid	tip
1	283.3	286.0	288.1	271.1	271.6	272.2
2	310.1	312.5	314.5	282.6	286.2	289.3
3	310.1	312.5	314.5	295.9	298.6	301.1

point	Entropy	Cp			Kappa	rho			a		
		hub	mid	tip	mid	hub	mid	tip	hub	mid	tip
1	99.93	1038.6	1038.7	1038.8	1.382	5.125	5.136	5.151	462.887	463.072	463.311
2	102.02	1041.0	1041.7	1042.4	1.381	5.367	5.454	5.531	467.417	468.789	469.996
3	103.32	1043.7	1044.3	1044.9	1.379	5.672	5.743	5.807	472.525	473.587	474.543

	deHaller			DF			Deq			Deq* Lieblein			Deq* Koch/Smith			Loss Coefficients Endwall	Loss Coefficients Profile
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip		
rotor	0.774	0.722	0.688	0.374	0.439	0.482	1.567	1.642	1.637	1.724	1.825	1.887	1.724	1.825	1.887	0.016	0.021
stator	0.720	0.726	0.727	0.424	0.436	0.454	1.619	1.635	1.662	1.788	1.806	1.832	1.788	1.806	1.832	0.011	0.020

	Mach relative			Mach critical			H/C	S/C			T/C			H/T
	hub	mid	tip	hub	mid	tip		hub	mid	tip	hub	mid	tip	
rotor	0.511	0.534	0.555	0.867	0.894	0.924	1.600	0.726	0.805	0.874	0.090	0.060	0.030	0.831
stator	0.501	0.490	0.477	0.896	0.894	0.893	2.000	0.676	0.751	0.806	0.060	0.060	0.060	0.838

	Nr.blades	Blade angles inlet			Blade angles outlet			Blade angles incidence		
		hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	68.00	51.71	57.59	62.79	16.20	22.82	30.24	-4.10	-5.87	-7.49
stator	96.00	48.40	54.44	60.61	15.53	17.02	16.78	-3.62	-5.68	-8.13

Blade angles

	deviation			camber			stagger			turning		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	8.74	9.22	9.18	35.51	34.77	32.56	29.86	34.33	39.02	22.67	19.68	15.89
stator	7.23	9.15	11.59	32.87	37.42	43.84	28.35	30.04	30.57	22.03	22.58	24.12

===== STAGE 11 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Isen	acc.Poly	Surge (Koch) Ch	Ch_max	Ch/Ch_max
1.149	0.550	122	0.365	0.562	24.332	3.217	0.926	0.924	0.929	0.440	0.462	0.953

point	radius			Velocities U			Cm			C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.348	0.383	0.415	240.4	264.7	286.9	155.8	149.6	143.1	168.9	166.6	162.6
2	0.349	0.383	0.414	241.5	264.7	286.0	161.8	147.8	133.8	229.5	225.3	220.3
3	0.351	0.383	0.413	N/A	N/A	N/A	151.7	146.1	140.3	165.3	163.6	160.2

point	Velocities W			C_theta			Angles Alpha			Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	233.3	242.8	251.9	66.7	73.4	79.6	22.76	26.15	28.37	48.11	51.97	55.38
2	180.0	175.6	173.9	162.8	170.0	175.0	45.16	48.99	52.59	25.93	32.64	39.68
3	N/A	N/A	N/A	65.7	73.6	77.3	23.41	26.74	28.86	N/A	N/A	N/A

point	Pressure Total			Static			Temperatures Total			Static		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	10.01	10.16	10.28	9.32	9.34	9.37	303.8	306.2	308.0	292.5	292.9	293.5
2	11.58	11.73	11.85	9.91	10.10	10.28	328.4	330.5	332.3	303.3	306.4	309.2
3	11.53	11.68	11.80	10.64	10.80	10.95	328.4	330.5	332.3	315.4	317.8	320.1

point	Enthalpy Total			Static		
	hub	mid	tip	hub	mid	tip
1	310.1	312.5	314.5	298.3	298.6	299.3
2	335.9	338.1	339.9	309.5	312.7	315.6
3	335.9	338.1	339.9	322.2	324.7	327.1

point	Entropy	Cp			Kappa	rho			a		
		hub	mid	tip	mid	hub	mid	tip	hub	mid	tip
1	103.32	1044.3	1044.3	1044.5	1.379	5.733	5.743	5.759	473.440	473.587	473.837
2	105.29	1046.7	1047.4	1048.0	1.378	5.985	6.068	6.146	477.723	478.915	480.019
3	106.53	1049.4	1050.0	1050.5	1.377	6.296	6.363	6.428	482.470	483.389	484.271

	deHaller			DF			Deq			Deq* Lieblein			Deq* Koch/Smith			Loss Coefficients Endwall	Loss Coefficients Profile
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip		
rotor	0.771	0.723	0.690	0.377	0.439	0.477	1.572	1.641	1.629	1.731	1.824	1.877	1.731	1.824	1.877	0.017	0.021
stator	0.720	0.726	0.727	0.425	0.436	0.454	1.621	1.635	1.663	1.790	1.806	1.833	1.790	1.806	1.833	0.012	0.020

	Mach relative			Mach critical			H/C	S/C			T/C			H/T
	hub	mid	tip	hub	mid	tip		hub	mid	tip	hub	mid	tip	
rotor	0.493	0.513	0.532	0.867	0.894	0.925	1.500	0.733	0.814	0.872	0.090	0.060	0.030	0.841
stator	0.480	0.470	0.459	0.896	0.894	0.893	1.830	0.691	0.758	0.816	0.060	0.060	0.060	0.847

	Nr.blades	Blade angles inlet			Blade angles outlet			Blade angles incidence		
		hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	68.00	52.53	58.21	63.12	17.11	23.30	30.49	-4.41	-6.24	-7.73
stator	92.00	49.26	54.99	61.04	15.95	17.49	17.16	-4.10	-6.01	-8.46

	Blade angles deviation			Blade angles camber			Blade angles stagger			Blade angles turning		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
rotor	8.82	9.34	9.19	35.42	34.91	32.62	30.40	34.51	39.07	22.18	19.33	15.70
stator	7.46	9.25	11.70	33.32	37.50	43.88	28.50	30.24	30.64	21.75	22.24	23.72

===== STAGE 12 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Efficiencies Isen	Efficiencies acc.Poly	Surge (Koch) Ch	Surge (Koch) Ch_max	Surge (Koch) Ch/Ch_max
1.137	0.550	122	0.358	0.554	23.296	3.079	0.923	0.922	0.929	0.438	0.464	0.945

point	radius			Velocities U			Velocities Cm			Velocities C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.346	0.379	0.409	239.5	262.1	282.9	152.1	146.1	139.9	165.8	163.6	159.7
2	0.348	0.379	0.408	240.4	262.1	282.1	157.8	144.4	131.0	225.1	221.1	216.3
3	0.349	0.379	0.407	N/A	N/A	N/A	148.2	142.7	137.1	162.3	160.6	157.3

point	Velocities W			Velocities C_theta			Angles Alpha			Angles Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	229.8	238.5	246.9	67.2	73.6	79.4	23.41	26.72	28.86	48.55	52.22	55.49
2	176.8	172.7	171.1	160.5	167.4	172.1	45.50	49.22	52.72	26.84	33.24	40.01
3	N/A	N/A	N/A	66.1	73.7	77.2	24.04	27.32	29.39	N/A	N/A	N/A

point	Pressure Total hub	Pressure Total mid	Pressure Total tip	Pressure Static hub	Pressure Static mid	Pressure Static tip	Temperatures Total hub	Temperatures Total mid	Temperatures Total tip	Temperatures Static hub	Temperatures Static mid	Temperatures Static tip
1	11.53	11.68	11.80	10.78	10.80	10.84	328.4	330.5	332.3	317.4	317.8	318.4
2	13.18	13.33	13.46	11.42	11.61	11.79	351.9	353.8	355.4	327.9	330.7	333.2
3	13.13	13.28	13.40	12.19	12.35	12.51	351.9	353.8	355.4	339.4	341.6	343.7

point	Enthalpy Total hub	Enthalpy Total mid	Enthalpy Total tip	Enthalpy Static hub	Enthalpy Static mid	Enthalpy Static tip
1	335.9	338.1	339.9	324.3	324.7	325.3
2	360.7	362.7	364.3	335.3	338.2	340.9
3	360.7	362.7	364.3	347.5	349.8	352.0

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	106.53	1049.9	1050.0	1050.1	1.377	6.353	6.363	6.380	483.257	483.389	483.622
2	108.42	1052.3	1053.0	1053.6	1.375	6.613	6.694	6.771	487.304	488.364	489.357
3	109.61	1055.0	1055.5	1056.0	1.374	6.929	6.994	7.058	491.725	492.546	493.340

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Deq* Lieblein mid	Deq* Lieblein tip	Deq* Koch/Smith hub	Deq* Koch/Smith mid	Deq* Koch/Smith tip	Loss Coefficients Endwall	Loss Coefficients Profile
rotor	0.770	0.724	0.693	0.381	0.438	0.475	1.580	1.639	1.623	1.738	1.822	1.872	1.738	1.822	1.872	0.019	0.021
stator	0.721	0.727	0.727	0.425	0.436	0.453	1.621	1.634	1.661	1.790	1.806	1.831	1.790	1.806	1.831	0.013	0.019

	Mach relative hub	Mach relative mid	Mach relative tip	Mach critical hub	Mach critical mid	Mach critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.476	0.493	0.511	0.867	0.894	0.925	1.400	0.751	0.823	0.884	0.090	0.060	0.030	0.849
stator	0.462	0.453	0.442	0.896	0.894	0.893	1.670	0.699	0.765	0.818	0.060	0.060	0.060	0.854

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	66.00	53.47	58.81	63.65	17.77	23.78	30.61	-4.91	-6.59	-8.15
stator	88.00	49.94	55.53	61.36	16.45	17.97	17.70	-4.44	-6.32	-8.64

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	9.07	9.47	9.40	35.69	35.03	33.03	30.71	34.70	38.98	21.71	18.98	15.48
stator	7.59	9.35	11.69	33.48	37.56	43.66	28.76	30.44	30.89	21.45	21.90	23.33

===== STAGE 13 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies			Surge (Koch)		
							Poly	Isen	acc.Poly	Ch	Ch_max	Ch/Ch_max
1.126	0.550	122	0.351	0.547	22.296	2.974	0.920	0.919	0.929	0.436	0.466	0.936

point	radius			Velocities								
				U			Cm			C		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	0.345	0.375	0.404	238.3	259.5	279.1	148.6	142.7	136.6	162.7	160.6	156.8
2	0.346	0.375	0.403	239.0	259.5	278.4	153.9	141.1	128.2	220.8	217.0	212.4
3	0.347	0.375	0.402	N/A	N/A	N/A	144.8	139.4	133.9	159.3	157.8	154.5

point	Velocities						Angles					
	W			C_theta			Alpha			Beta		
	hub	mid	tip	hub	m	tip	hub	mid	tip	hub	mid	tip
1	226.2	234.3	242.1	67.7	73.7	79.2	24.04	27.30	29.39	48.95	52.47	55.64
2	173.8	169.9	168.3	158.3	164.9	169.3	45.80	49.44	52.88	27.69	33.85	40.41
3	N/A	N/A	N/A	66.5	73.8	77.1	24.66	27.90	29.93	N/A	N/A	N/A

point	Pressure						Temperatures					
	Total			Static			Total			Static		
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip
1	13.13	13.28	13.40	12.33	12.35	12.39	351.9	353.8	355.4	341.3	341.6	342.2
2	14.86	15.01	15.14	13.01	13.20	13.39	374.4	376.1	377.6	351.4	353.9	356.3
3	14.80	14.95	15.08	13.82	13.98	14.14	374.4	376.1	377.6	362.4	364.4	366.3

point	Enthalpy					
	Total			Static		
	hub	mid	tip	hub	mid	tip
1	360.7	362.7	364.3	349.4	349.8	350.4
2	384.5	386.3	387.9	360.1	362.8	365.3
3	384.5	386.3	387.9	371.8	373.9	375.9

point	Entropy	Cp			Kappa	rho			a		
		hub	mid	tip	mid	hub	mid	tip	hub	mid	tip
1	109.61	1055.5	1055.5	1055.7	1.374	6.984	6.994	7.012	492.426	492.546	492.764
2	111.42	1057.9	1058.5	1059.0	1.372	7.250	7.330	7.405	496.246	497.200	498.100
3	112.59	1060.5	1061.0	1061.4	1.371	7.569	7.633	7.695	500.375	501.115	501.836

	deHaller			DF			Deq			Deq*						Loss Coefficients	
										Lieblein			Koch/Smith			Endwall	Profile
	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip	hub	mid	tip		
rotor	0.768	0.725	0.695	0.382	0.437	0.472	1.582	1.637	1.616	1.741	1.820	1.863	1.741	1.820	1.863	0.020	0.021
stator	0.722	0.727	0.727	0.425	0.435	0.452	1.620	1.633	1.659	1.790	1.805	1.830	1.790	1.805	1.830	0.014	0.019

	Mach relative hub	Mach relative mid	Mach relative tip	Mach critical hub	Mach critical mid	Mach critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.459	0.476	0.491	0.867	0.895	0.925	1.300	0.759	0.833	0.887	0.090	0.060	0.030	0.856
stator	0.445	0.436	0.426	0.896	0.895	0.893	1.500	0.708	0.773	0.823	0.060	0.060	0.060	0.860

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	64.00	54.16	59.39	64.03	18.53	24.25	30.97	-5.22	-6.92	-8.40
stator	82.00	50.57	56.06	61.75	16.94	18.46	18.21	-4.77	-6.61	-8.87

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	9.16	9.59	9.44	35.63	35.13	33.06	31.13	34.90	39.10	21.26	18.62	15.23
stator	7.71	9.45	11.72	33.63	37.60	43.53	28.98	30.64	31.11	21.14	21.54	22.94

===== STAGE 14 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Efficiencies Isen	Efficiencies acc.Poly	Surge (Koch) Ch	Surge (Koch) Ch_max	Surge (Koch) Ch/Ch_max
1.116	0.550	122	0.345	0.540	21.331	2.898	0.916	0.915	0.928	0.433	0.467	0.926

point	radius hub	radius mid	radius tip	Velocities U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.343	0.372	0.399	236.8	256.9	275.5	145.2	139.4	133.5	159.7	157.8	154.0
2	0.344	0.372	0.398	237.5	256.9	274.9	150.2	137.8	125.3	216.5	212.9	208.4
3	0.344	0.372	0.397	N/A	N/A	N/A	141.5	136.2	130.7	156.5	155.0	151.7

point	Velocities W hub	W mid	W tip	C_theta hub	C_theta m	C_theta tip	Angles Alpha hub	Alpha mid	Alpha tip	Beta hub	Beta mid	Beta tip
1	222.6	230.1	237.4	68.0	73.8	79.1	24.66	27.88	29.93	49.30	52.71	55.80
2	170.9	167.1	165.6	156.0	162.3	166.6	46.07	49.67	53.05	28.48	34.45	40.85
3	N/A	N/A	N/A	66.8	73.8	77.0	25.26	28.48	30.50	N/A	N/A	N/A

point	Pressure Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	14.80	14.95	15.08	13.95	13.98	14.02	374.4	376.1	377.6	364.1	364.4	364.9
2	16.60	16.75	16.88	14.67	14.87	15.06	395.8	397.4	398.8	373.8	376.2	378.4
3	16.54	16.69	16.81	15.51	15.67	15.83	395.8	397.4	398.8	384.3	386.2	388.0

point	Enthalpy Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
1	384.5	386.3	387.9	373.6	373.9	374.5
2	407.3	409.1	410.5	383.9	386.4	388.8
3	407.3	409.1	410.5	395.1	397.1	399.0

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	112.59	1060.9	1061.0	1061.1	1.371	7.623	7.633	7.650	501.004	501.115	501.320
2	114.34	1063.2	1063.8	1064.3	1.370	7.893	7.970	8.045	504.609	505.476	506.299
3	115.48	1065.7	1066.2	1066.6	1.369	8.212	8.275	8.336	508.473	509.146	509.807

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Deq* Lieblein mid	Deq* Lieblein tip	Deq* Koch/Smith hub	Deq* Koch/Smith mid	Deq* Koch/Smith tip	Loss Coefficients Endwall	Loss Coefficients Profile
rotor	0.768	0.726	0.698	0.383	0.436	0.469	1.584	1.635	1.610	1.743	1.818	1.857	1.743	1.818	1.857	0.022	0.021
stator	0.723	0.728	0.728	0.425	0.435	0.450	1.619	1.632	1.657	1.789	1.804	1.828	1.789	1.804	1.828	0.016	0.019

	Mach relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.444	0.459	0.474	0.867	0.895	0.925	1.200	0.770	0.843	0.894	0.090	0.060	0.030	0.862
stator	0.429	0.421	0.412	0.896	0.895	0.893	1.330	0.716	0.782	0.828	0.060	0.060	0.060	0.865

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	61.00	54.85	59.95	64.47	19.20	24.73	31.32	-5.55	-7.24	-8.67
stator	75.00	51.14	56.57	62.13	17.45	18.94	18.76	-5.07	-6.90	-9.08

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	9.28	9.72	9.53	35.64	35.22	33.15	31.48	35.10	39.22	20.82	18.26	14.95
stator	7.81	9.54	11.74	33.69	37.63	43.37	29.23	30.85	31.37	20.81	21.18	22.55

===== STAGE 15 =====

PR	REACT	Flow	PSI	PHI	dT0	dS	Efficiencies Poly	Efficiencies Isen	Efficiencies acc.Poly	Surge (Koch) Ch	Surge (Koch) Ch_max	Surge (Koch) Ch/Ch_max
1.107	0.550	122	0.338	0.533	20.401	2.850	0.911	0.910	0.928	0.429	0.469	0.915

point	radius hub	radius mid	radius tip	Velocities U hub	U mid	U tip	Cm hub	Cm mid	Cm tip	C hub	C mid	C tip
1	0.340	0.368	0.394	235.2	254.3	272.0	141.9	136.2	130.3	156.9	155.0	151.2
2	0.341	0.368	0.393	235.7	254.3	271.5	146.7	134.6	122.4	212.4	209.0	204.6
3	0.342	0.368	0.392	N/A	N/A	N/A	138.3	133.1	127.6	153.7	152.2	149.0

point	Velocities W hub	Velocities W mid	Velocities W tip	Velocities C_theta hub	Velocities C_theta m	Velocities C_theta tip	Angles Alpha hub	Angles Alpha mid	Angles Alpha tip	Angles Beta hub	Angles Beta mid	Angles Beta tip
1	219.0	226.1	232.9	68.3	73.8	79.0	25.26	28.46	30.50	49.62	52.95	55.98
2	168.1	164.5	163.0	153.6	159.8	163.9	46.32	49.89	53.25	29.23	35.05	41.33
3	N/A	N/A	N/A	67.0	73.9	76.9	25.84	29.07	31.09	N/A	N/A	N/A

point	Pressure Total hub	Pressure Total mid	Pressure Total tip	Pressure Static hub	Pressure Static mid	Pressure Static tip	Temperatures Total hub	Temperatures Total mid	Temperatures Total tip	Temperatures Static hub	Temperatures Static mid	Temperatures Static tip
1	16.54	16.69	16.81	15.65	15.67	15.72	395.8	397.4	398.8	385.9	386.2	386.7
2	18.40	18.55	18.68	16.39	16.59	16.79	416.3	417.8	419.1	395.3	397.5	399.6
3	18.33	18.48	18.60	17.26	17.42	17.58	416.3	417.8	419.1	405.3	407.0	408.7

point	Enthalpy Total hub	Enthalpy Total mid	Enthalpy Total tip	Enthalpy Static hub	Enthalpy Static mid	Enthalpy Static tip
1	407.3	409.1	410.5	396.8	397.1	397.6
2	429.3	430.9	432.3	406.7	409.1	411.3
3	429.3	430.9	432.3	417.5	419.3	421.2

point	Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
1	115.48	1066.1	1066.2	1066.3	1.369	8.265	8.275	8.293	509.043	509.146	509.341
2	117.19	1068.4	1068.9	1069.4	1.367	8.536	8.613	8.687	512.444	513.238	513.996
3	118.33	1070.8	1071.2	1071.6	1.366	8.855	8.917	8.978	516.067	516.684	517.294

	deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Deq* Lieblein mid	Deq* Lieblein tip	Deq* Koch/Smith hub	Deq* Koch/Smith mid	Deq* Koch/Smith tip	Loss Coefficients Endwall	Loss Coefficients Profile
rotor	0.768	0.728	0.700	0.384	0.435	0.467	1.586	1.632	1.606	1.746	1.816	1.852	1.746	1.816	1.852	0.024	0.021
stator	0.724	0.728	0.728	0.425	0.434	0.451	1.619	1.630	1.657	1.789	1.803	1.829	1.789	1.803	1.829	0.018	0.019

	Mach relative hub	Mach relative mid	Mach relative tip	Mach critical hub	Mach critical mid	Mach critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.430	0.444	0.457	0.867	0.895	0.925	1.100	0.785	0.854	0.906	0.090	0.060	0.030	0.866
stator	0.415	0.407	0.398	0.896	0.895	0.893	1.170	0.731	0.791	0.840	0.060	0.060	0.060	0.869

	Nr.blades	Blade angles inlet hub	Blade angles inlet mid	Blade angles inlet tip	Blade angles outlet hub	Blade angles outlet mid	Blade angles outlet tip	Blade angles incidence hub	Blade angles incidence mid	Blade angles incidence tip
rotor	57.00	55.56	60.50	64.98	19.77	25.21	31.64	-5.93	-7.56	-9.01
stator	67.00	51.76	57.07	62.69	17.86	19.43	19.17	-5.44	-7.18	-9.44

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===== STAGE 16 =====
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PR      REACT    Flow   PSI     PHI     dT0      dS      ------Efficiencies------    --------Surge (Koch)------
                                                         Poly    Isen    acc.Poly    Ch      Ch_max   Ch/Ch_max
1.099   0.550    122    0.331   0.526   19.503   2.838   0.905   0.904   0.927       0.428   0.472    0.905

point   ------radius-------    ------------------------------Velocities--------------------------------------
                                **********U************   *********Cm***********    ***********C**********
          hub     mid    tip     hub      mid      tip     hub      mid      tip      hub      mid      tip
   1    0.338   0.364   0.389   233.3    251.7    268.7   138.7    133.1    127.2    154.1    152.2    148.5
   2    0.338   0.364   0.388   233.8    251.7    268.3   143.4    131.5    119.5    208.4    205.1    200.7
   3    0.339   0.364   0.388   N/A      N/A      N/A     135.3    130.0    124.5    151.0    148.7    146.3

point    -----------------------Velocities------------------------   --------------------Angles-----------------------------
         ***********W***********    **********C_theta************   ************Alpha******    *************Beta************
          hub      mid      tip       hub      m        tip        hub      mid      tip      hub      mid      tip
   1     215.4    222.0    228.5     68.5     73.9     78.9       25.84    29.05    31.09    49.91    53.18    56.17
   2     165.4    161.9    160.4     151.3    157.3    161.3      46.54    50.10    53.47    29.93    35.65    41.85
   3      N/A      N/A      N/A      67.2     72.2     76.9       26.42    29.05    31.70     N/A      N/A      N/A

point   --------------------Pressure-------------------    -----------------Temperatures------------------
        ********Total********    ********Static********    ********Total********    *********Static*********
         hub     mid     tip       hub     mid     tip      hub     mid     tip      hub        mid      tip
   1    18.33   18.48   18.60     17.40   17.42   17.47    416.3   417.8   419.1    406.8      407.0    407.6
   2    20.24   20.39   20.51     18.16   18.37   18.56    435.9   437.3   438.5    415.7      417.8    419.8
   3    20.16   20.31   20.43     19.05   19.23   19.38    435.9   437.3   438.5    425.3      427.1    428.6

point   -------------------------Enthalpy-------------------------
        ************Total************     *********Static********
         hub         mid        tip        hub      mid      tip
   1    429.3       430.9      432.3      419.0    419.3    419.9
   2    450.4       451.9      453.2      428.7    430.9    433.0
   3    450.4       451.9      453.2      439.0    440.9    442.5

point       Entropy     -----------Cp------------      ----Kappa----     --------rho--------        ------------a-------------
                        hub         mid        tip          mid          hub     mid     tip          hub         mid         tip
   1        118.33      1071.2      1071.2     1071.3       1.366        8.907   8.917   8.935        516.587     516.684     516.870
   2        120.02      1073.3      1073.8     1074.3       1.365        9.178   9.254   9.327        519.795     520.527     521.231
   3        121.17      1075.6      1076.1     1076.4       1.364        9.495   9.560   9.616        523.197     523.809     524.333

         ---deHaller---     --------DF---------     --------Deq--------     --------------------Deq*--------------------   Loss Coefficients
                                                                            ******Lieblein*****      *****Koch/Smith*****    Endwall  Profile
          hub   mid   tip    hub      mid     tip    hub     mid     tip     hub     mid     tip      hub     mid     tip
rotor  0.768 0.729 0.702    0.383    0.434   0.463  1.584   1.629   1.599   1.745   1.813   1.845    1.745   1.813   1.845    0.026    0.021
stator 0.725 0.725 0.729    0.420    0.437   0.444  1.610   1.637   1.646   1.781   1.810   1.819    1.781   1.810   1.819    0.021    0.019
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	Mach relative hub	Mach relative mid	Mach relative tip	Mach critical hub	Mach critical mid	Mach critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C hub	T/C mid	T/C tip	H/T
rotor	0.417	0.430	0.442	0.867	0.895	0.925	1.000	0.793	0.866	0.911	0.090	0.060	0.030	0.870
stator	0.401	0.394	0.385	0.896	0.895	0.894	1.000	0.718	0.781	0.823	0.060	0.060	0.060	0.873

	Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
rotor	53.00	56.09	61.04	65.38	20.42	25.68	32.14	-6.17	-7.86	-9.21
stator	60.00	51.90	57.39	62.67	18.66	19.38	20.19	-5.36	-7.29	-9.20

	Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip	turning hub	turning mid	turning tip
rotor	9.51	9.97	9.71	35.67	35.36	33.25	32.08	35.50	39.55	19.98	17.53	14.33
stator	7.76	9.67	11.51	33.24	38.01	42.48	29.92	31.10	32.23	20.12	21.05	21.77

===== OUTLET GUIDE VANE=====

radius hub	radius rms	radius tip	Velocities Cm hub	Cm rms	Cm tip
0.339	0.364	0.388	135.26	130.00	124.51

Pressure Total hub	Total mid	Total tip	Static hub	Static mid	Static tip	Temperatures Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
20.38	20.26	20.11	19.22	19.43	19.62	435.93	437.34	438.50	427.44	429.50	431.31

Enthalpy Total hub	Total mid	Total tip	Static hub	Static mid	Static tip
450.4	451.9	453.2	441.2	443.5	445.4

Entropy	Cp hub	Cp mid	Cp tip	Kappa mid	rho hub	rho mid	rho tip	a hub	a mid	a tip
121.83	1076.156	1076.653	1077.091	1.364	9.551	9.629	9.697	523.938	524.662	525.299

deHaller hub	deHaller mid	deHaller tip	DF hub	DF mid	DF tip	Deq hub	Deq mid	Deq tip	Deq* Lieblein hub	Lieblein mid	Lieblein tip	Koch/Smith hub	Koch/Smith mid	Koch/Smith tip	Loss Coefficients Endwall	Profile
0.896	0.874	0.851	0.263	0.313	0.364	1.321	1.391	1.466	1.444	1.510	1.578	1.413	1.485	1.563	0.027	0.016

Mach relative hub	relative mid	relative tip	critical hub	critical mid	critical tip	H/C	S/C hub	S/C mid	S/C tip	T/C	H/T
0.258	0.284	0.237	0.895	0.893	0.892	1.000	0.714	0.772	0.817	0.060	0.873

Nr.blades	Blade angles inlet hub	inlet mid	inlet tip	outlet hub	outlet mid	outlet tip	incidence hub	incidence mid	incidence tip
61.00	32.08	35.79	39.52	-7.99	-9.84	-11.75	-5.66	-6.74	-7.83

Blade angles deviation hub	deviation mid	deviation tip	camber hub	camber mid	camber tip	stagger hub	stagger mid	stagger tip
7.99	9.84	11.75	40.07	45.63	51.27	6.38	6.23	6.06