DESIGN OPTIMIZATION OF AN AXIAL FLOW COMPRESSOR FOR INDUSTRIAL GAS TURBINE

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Abstract

In recent decade, industry had started to use intensively 3D simulation in compressor flow path and its components design. Designing an Axial Compressor is more an art than science, because one has to vary the parameters by his intuition. Slight variation in one parameter may lead to large variation in another parameter. There are several options to improve the design but it requires enormous time and effort, as each step of designing and analysis is pretty time consuming. Further this design can be optimized with several options available. This paper reports design and optimization of an axial flow compressor, using a uniform approach to solution on theoretical design problems. Preliminary design was carried out for a set of design parameters and tested for stall at different speed and mass flow rate for given pressure ratio. Modeling was performed using 1D and 2D simulations, as the loss parameters were in limits blade modeling was done using blade profiling and 2D analysis. 3D simulation both CFD and FEA were performed. The results of optimized design shown a close agreement with the theoretical design in terms of mass flow rate at given speed for rated pressure ratio with wide stall margin at low losses in less time for limited given input.

Keywords: CFD Analysis, Optimization of axial flow compressor etc…

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1. NOMENCLATURE

1D one-dimensional
2D two-dimensional
3D three-dimensional
CFD computational fluid dynamics
FEM finite elements method
G : Mass flow rate in Kg/s
M: Mach number
AR: Aspect ratio
C: Blade chord in m
S: Blade spacing in m
Ht: Blade height in m
R: Gas constant in J/Kg-K
γ: Ratio of specific heat.
Cp: Specific heat at constant pressure in J/Kg-K
N: Power requirement in watt
n_: Rotational speed in rpm
Tr: Torque requirement in N-m
U: Blade speed in m/s
V: Flow velocity in m/s
β: Flow angle in deg

2. PROBLEM STATEMENT

Now a days, turbo machine elements design using integrated software is developing intensively [11, 12, 13]. Simplified models of computation (1D/2D) [11,14] as well as precise full-dimensional ones [15] can be used in such systems. A comparison of aerodynamic computational results using carefully selected 1D/2D models and CFD analysis with experimental data [13,14] is evidence of simplified calculations and adequate accuracy for preliminary design.

This study aims at optimization of aerodynamic design of an axial flow compressor for gas turbine engine for process industries. Design specification and assumptions for Stage Design are

Mass Flow rate at Atmospheric condition 4.91 kg/sec

Rotor speed	27000 RPM
Inlet total Temperature	288 K
Inlet total Pressure	101325 N/m^2
No. of Stages	5

3. PRELIMINARY DESIGN

Preliminary design solution generator helps to rapidly select optimal main flow path parameters, such as the number of stages, geometrical dimensions and angles, heat drop distributions etc. Preliminary design procedure performs inverse task calculation i.e. based on boundary conditions and calculates flow path geometry. Preliminary design starts from specification of technical requirement, setting up design task and compressor conceptual layout that includes:
• Inlet and outlet boundary conditions such as inlet pressure, temperature, pressure ratio etc.
• Conceptual design and sizing layout i.e. quantity of modules inside compressor, number of stages in each group, meridional and axial sizes limitations, work coefficient.
• The designer has to decide what kind of geometrical parameters should be used as design constraints, i.e. specific diameter and its ranges or exact value, and blade heights or angles based on requirements or assumptions.

To perform compressor preliminary design first it's necessary to specify the Machine's parameters :

• Inlet and outlet condition type and values.
• Design criterion i.e. power and choice of efficiencies.
• Number of modules.

Next step needs design data. The available options are specific diameter, range of search points i.e. number of possible design solutions that will be considered, outlet pressure, use of IGV or OGV, design parameters ranges or exact values. Module constraints are number of stages and axial length limitations. Obtaining possible designs within the given data and constraints, the results of simulations will be as shown in Fig. 1 are
a. Generated designs
b. Solutions review table
• Best in space • Best in show • Applied solution • Picked solution

As it can be clear, this is just a rough estimation and overview of overall possible designs; to fine tune and adjust the obtained solution according to requirements using the Design Space Explorer.
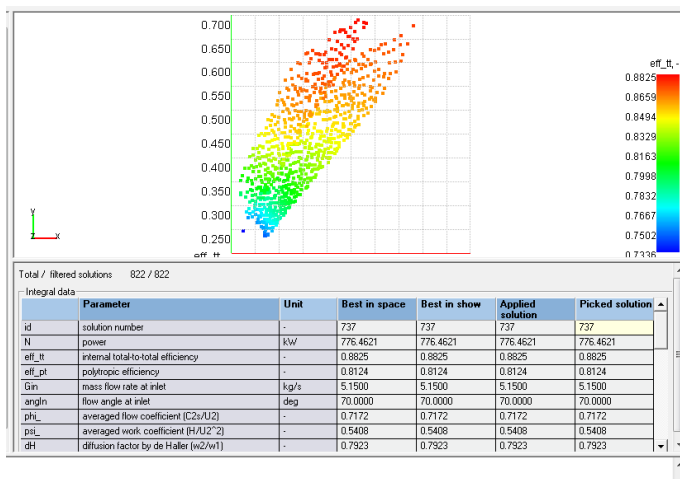

Fig. 1 Design Space Explorer

4. COMPRESSOR PERFORMANCES VALIDATION ON PRELIMINARY DESIGN PHASE

Preliminary Design phase is completed and having couple of points on PD space which correspond to design requirements. It needs to choose optimal one among them to move ahead with it. The best efficiency in shown space is provided by point #737. It is reasonable to choose it as a current design. The aim is to verify performances of created flow path on design mode and adjust them if it's necessary by rerunning preliminary design with different settings to match design point or some certain operation ranges criteria.

5. PERFORMANCES MAP GENERATION FOR DESIGN POINT IN PD MAP

PDMAP helps to evaluate the created design performances on speed line. PD MAP is the tool to calculate compressor curves necessary for initial compressor characteristics assessment. This stage of design process needs to check the coincidence of the speed line with design point and evaluate gas dynamic stability ranges to ensure, that one can move ahead with created design. Check and edit inlet and outlet pressure range. Run calculation and see its results on visualized Map. This calculated performances map shows the difference between designed compressor performances and target design point. Designer can make a decision to redesign compressor on different performances and match design point, therefore it's necessary to increase or decrease mass flow rate in preliminary design. To shift gas dynamic stability ranges relatively to design point it's necessary to change pressure ratio in preliminary design. The difference in acceptable range proceed with current results. Filter solutions basing on the same criteria (flow coefficient, work coefficient ranges, maximal Mach number), and save best solution as new design replacing existing one.
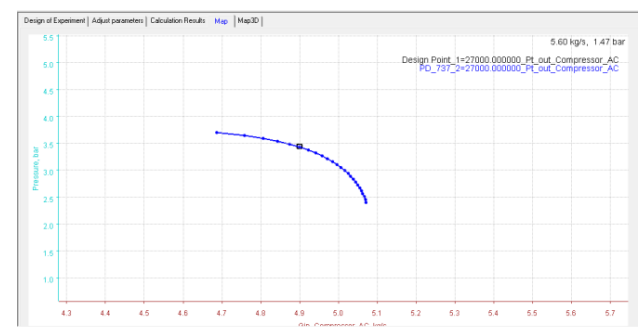

Fig 2 Performance curve of Compressor

The performance characteristic curve obtained in AXMAP is shown in Fig.2. indicates the compressor is matching the performance i.e. delivering the given mass of air at designed outlet pressure not only this, the compressor having sufficiently wide range for stall and choke margin. The choking range at designed RPM is 2.2 bar and stalling range is 3.7 bar.

5.1 Post-Design: Compressor Flow Path Editing

Flow Path editing is done in post design using Inverse Design Task as solver it means that specified boundary conditions and mass flow rate are preserved while changing flow path geometry and the options for this are
• specific diameter.
• aspect ratio and chords values.

Flow path can be edited by editing blade heights at outlet and specific diameters at outlet. Available editing points depend on the selected specific diameter. Interactive meridional shapes adjustments can be performed by adjusting the distribution of flow path specific diameters using spline. It performs simultaneous adjustment of specific diameters of the whole flow path at once. Adjusting spline is defined with 4 control points. When a specific diameter changes, the inverse design task recalculates blade

heights and metal angles. Post-design geometry adjustment can be done to control number of blades, chords and aspect ratio by keeping solidity (relative pitch) near the value, selected by preliminary design.
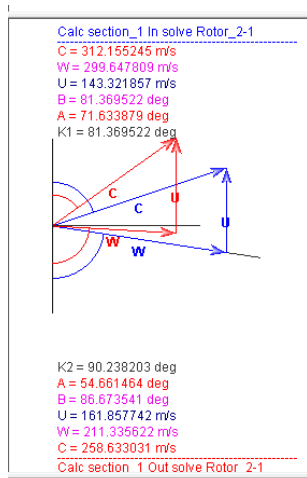

Fig. 3 Velocity Triangle for section

Post design shows velocity triangle and HS Diagram for respective section. Fig. 3 and Fig. 4 shows the velocity triangle and HS Diagram for section 1 of machine which indicates smooth flow turning i.e. no excessive turning of blades.
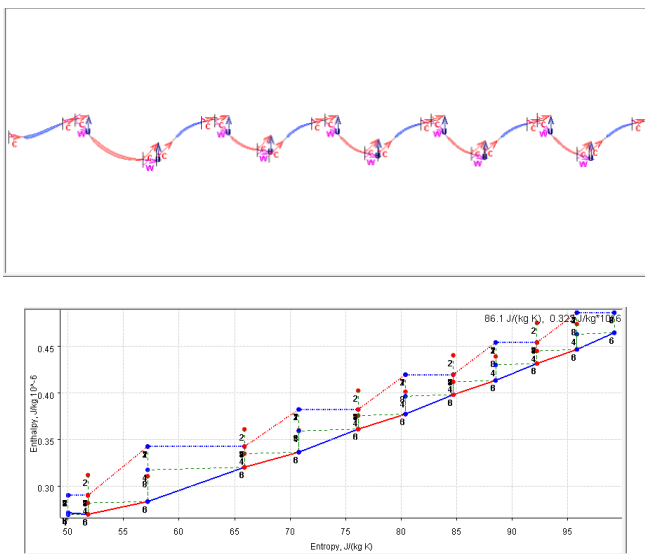

Fig. 4 H.S. Diagram

6 STREAMLINE CALCULATIONS

Streamline calculation task can be accomplished by two modes
• meanline mode
• streamline mode

Meanline Calculation

Once the design task is over, estimation of design results by performing benchmarking calculation in Streamline solver with formulations that preserve the geometry:
• Find MFR (mass flow rate) for given inlet total pressure and outlet total/static pressure
• Find total/static outlet pressure for given MFR

It is assumed that the designed procedures are finished, i.e. has 1 section, so solver runs mean line analysis task. This gives an accurate performance estimation, i.e. power, efficiency, mass flow rate. The next step is to consider some supplemental design details that can't be taken into account during design need to be clarified i.e.
• detailed clearance data
• type and location of extractions, injections

Using Streamline solver for 1D and 2D calculations the parameters obtained are shown in Fig. 6 and Fig. 7. The variation of Parameters such as absolute and relative Mach No., Total Pressure Ratio Diffusion Factor and Total loss coefficient shows a very good agreement between design and computation results.
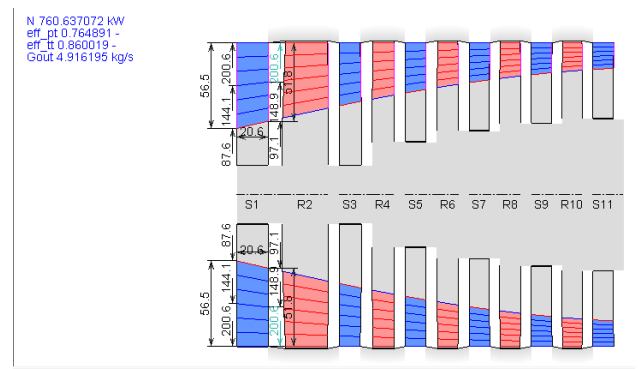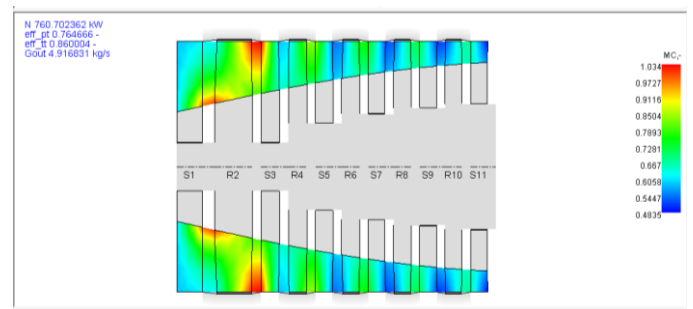

Fig. 5 Dimensions of Machine

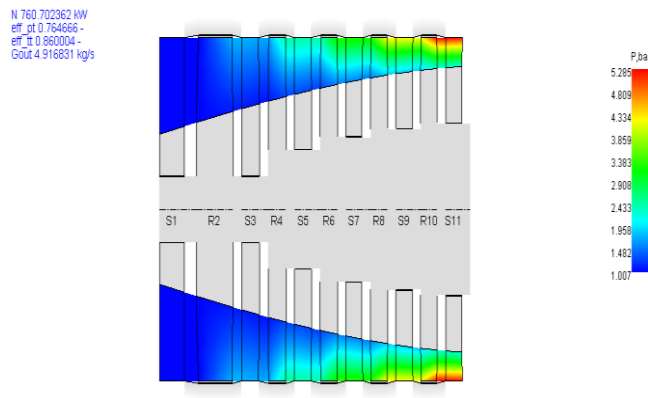**Fig. 6** Variation of Mach No. along Machine for 2D computations

Fig.7 Variation of Pressure along Machine for 2D computations

7. OFF-DESIGN PERFORMANCES CALCULATIONS WITH AxMAP

AxMAP is a multi-run tool to run a series of calculations for 2 variables (additional variables can be used as parameters). AxMAP is very effective tool to study the influence of operational parameters on compressor off-design performance. Also it is the ultimate tool to calculate compressor curves that are necessary for turbine-compressor matching. Setting up the map calculations by selecting variables such as rotation speed, total outlet pressure and objectives as power, total-to-total efficiency, mass flow rate and volume flow rate at outlet, total-static and total pressure ratio.

Further Selecting objectives and design variables and ranges

Rotational speed as primary variable, setting number of points (speedlines) to 5 and ranges from 24300 to 29700 RPM

For total outlet pressure setting it as row while the number of points equals to 10 and ranges from 2.5 to 4.0 bar after finishing the calculations, the results are shown in Fig. 7.

7.1 Diffusion Factor and Stall Prediction

The crucial questions for all compressor designer is how to predict, where (at which rows) stall possibility is highest for current operating mode. AxMAP can be used for this kind of prediction, using indirect, but very accurate criterion of diffusion factor. To estimate diffusion factor on different operating modes for stages in compressor. The off design performance of an axial flow compressor is evaluated using AXMAP by selecting variables as Total outlet pressure and RPM whereas Power, Mass flow inlet, Total Pressure ratio and efficiency as objectives, which indicated a wide operation range as shown in Fig.8. with the diffusion factor ranges from 0.44 to 0.39 and Dehaller No. from 0.69 to 0.78.
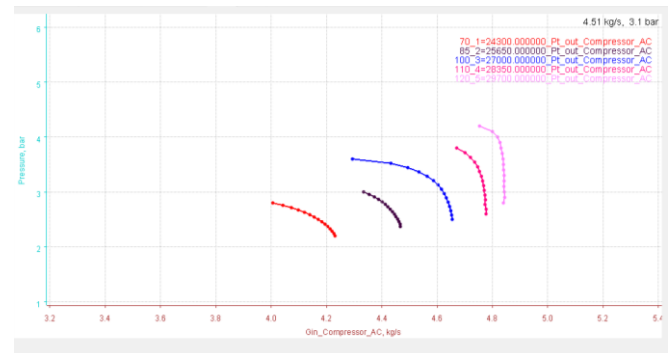

Fig. 8 off Design Performance of Compressor

8. PROFILING ON PLAIN SECTIONS

8.1 Custom Camber line Profiling Method

In camber line profiling mode a profile shape is generated by two B-splines:
• camber line spline
• thickness spline

Thickness spline forms a symmetrical profile which has camber line curves along with the spline curvature.

Following are the main editing approaches:
a. Parameters manual editing in profiling grid
b. Editing of angles with profiling pane
c. Splines editing of camber line curvature
d. Splines editing of thickness

To control profiling quality, different kinds of charts are available:
• Mach number
• Relative pressure
• Profile curvature
• Momentum thickness (boundary layer characteristic criterion)
• Loading (from pressure) (only in Stream wise mode)
• Loading (from velocity) (only in Streamwise mode)

Checking off design performance, blade designing performed using custom camber profiling option and adjusting the profile so that it shows a value less than 0.05 for burii chart, proper Mach No. distribution, Curvature and boundary layer thickness. CFD computations are performed and it shows the variation of parameters such as absolute and relative Mach No., Total and static Pressure , Total and Static Temperature shows very good agreement with the design intent as shown in Fig. 9

9. 3D BLADE DESIGN AND STACKING

3D blade design is performed in the Profiling. In the course of 3D design procedure, smoothing the geometrical parameters along height and stacking axis redistribution are available. When profiling on individual sections is finished, checking smoothness and adjusting parameters distribution along the blade on Blade 3D plane.

Blades 3D design objectives
• Provide smooth distribution of angles and other geometrical parameters
• Provide desired blade meridional outline
• Provide smooth stress distribution along blade height within margins of admissible stress
Two main types of blade design can be distinguished:
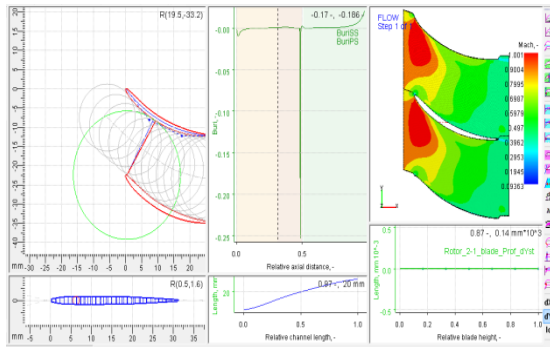• prismatic blade
• twisted blade

Fig. 9 Blade Profiling and CFD Analysis

10. 3D STRUCTURAL AND MODAL ANALYSIS IN AxSTRESS

Structural calculations are performed by previewing the mesh and determining the desired mesh quality. The number of elements that will be used in selected mesh is presented in calculation log. In structural analysis setup, setting mesh quality and type of aerodynamic loads (from compressible or incompressible fluid), then selecting whether to calculate or not the centrifugal loads and set the number of natural frequencies for modal analysis. Performing calculations and finding its results as stresses distribution and natural frequencies from modal analysis. Blade color gradient is chosen according to maximal and minimal stresses. But there are stress concentrators, and it's necessary to exclude them from consideration to see distribution of stresses normally. Further Calculations can be performed for different number of blades in package and increase mesh quality. In the same manner, after switching rows by arrows, and can calculate stresses for nozzles and stator diaphragm body.

10.1 Campbell Diagram Calculation

Campbell diagram shows how ware provides both rotating and stationary reference frames vibration modes split because of whirling. The primary application for a diagram assists users in finding the critical speed for a stationary frame of reference. This is a case in which a rotating synchronous or asynchronous force as a function structure (rotor) is modeled along with a stationary support of rotation speed.
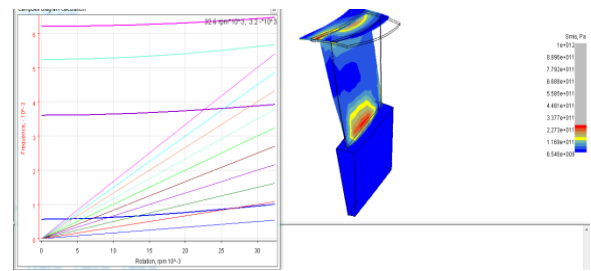

Fig. 10 Stress and Campbell Diagram

The FEA simulations are performed using AXSTRESS at different frequency level which shows stress level within range but Campbell diagram indicates one of the natural frequency crosses the mode of operation indicates the compressor needs rotor dynamics to have dynamic balancing and safe operation as shown in Fig. 10.

11. 3D FLOW ANALYSIS WITH AxCFD

To evaluate designed blades in 3D CFD, AxCFD embedded into AxSTREAM as a express flow analysis with full Navier-Stocks capabilities and automatic mesh-generation.

11.1 3D Flow Calculations Objectives

• Evaluate designed flow path quality
• Compare results between 3D CFD, Streamline solver
• Checking presence of separations, supersonic shocks, other effects that can be investigated only in 3D calculation.
3D CFD solver needs following inputs
• Mesh quality – setting that provides the user with an opportunity to change mesh quality in blade-to-blade and hub-to-shroud surfaces
• Flow time, relative time sub step and number of calculation steps – solver convergence control settings and number of calculation steps
• Use previous result – use previous calculation step results as initial values for a new calculation
• HO-mesh – makes H-O quality mesh nearby airfoil surface
• Calculate for given MFR – use constant MFR in calculation (mainly for compressor calculation) to converge to outlet pressure value. Mass flow rate value need to be specified in corresponding field.
• CFD order – improves calculation accuracy through more accurate approximation in finite-elements, by inputing numbers from 1 to 2.
• Viscosity – enables viscosity influence on calculation results
• Turbulence models – choice of turbulence models and level of turbulence
• Channel extension – setup channel extension length in percentage

Selecting the whole machine for calculation.
Performing the calculations first with coarse mesh quality for quick convergence and rough prediction and then with fine mesh, viscosity, turbulence level and completing the calculations when the target mass flow reached i.e. inlet mass flow rate is equal to outlet mass flow rate. Fig. 11, 12, 13, 14 shows variation of flow parameters through machine

Such as Pressure, Mach No. very close to the design intend with achieving the objective of optimization through AXSTREAM for wide choke and stall margin.
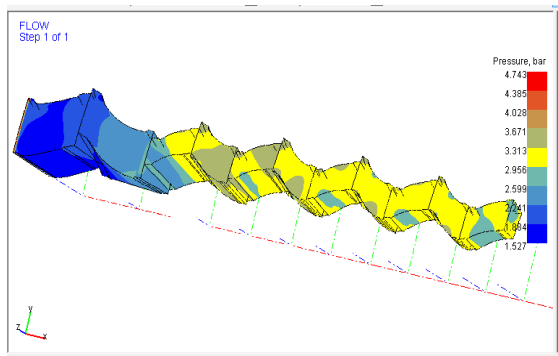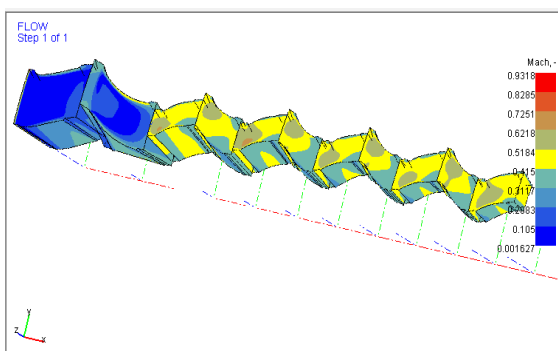

Fig. 11 Variation of Pressure

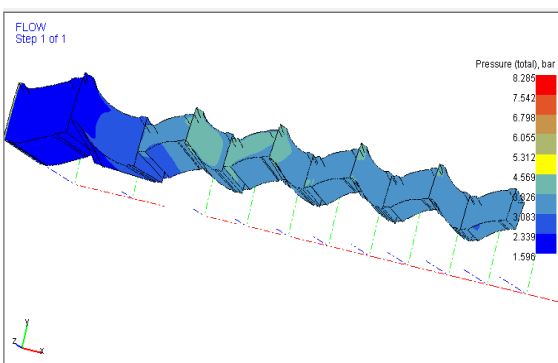**Fig 12** Variation Mach No
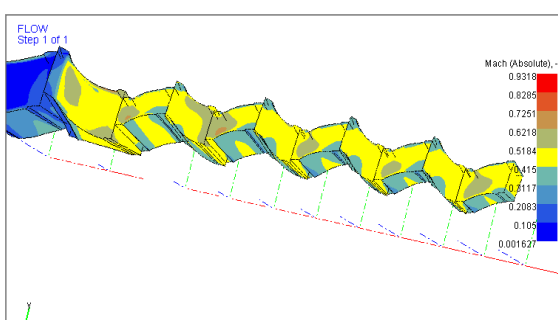

Fig 13 Variation of Total Pressure

Fig 14 Variation of Absolute Mach No

12. CONCLUSIONS

The optimization of aerodynamic design for an axial flow compressor of a gas turbine engine is achieved using AXSTREAM. Stage exit average pressure ratio and Mach. No. are matching with the design intent. The diffusion factor and Dehaller no. are in the allowable range for both rotor and stator throughout the machine. The total loss coefficient is in the range of 0.03 to 0.08 for both rotor and stator. The 2D CFD results at respective section in terms of Mach No. absolute pressure are matching with the design values. The FEA calculations performed using AXSTRESS and it has been observed that the stresses are in allowable range but Campbell diagram shows that one of the natural frequencies crossing the mode of operation means Rotor Dynamic Analysis is to be carried out to avoid structural failure of design.

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