Design optimization of an axial flow compressor using CFD approach and experimental validation

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Abstract : This paper deals with aerodynamic design of a single stage axial flow compressor for gas turbine engine. The axial flow compressor is designed for the constant tip diameter of the compressor rotor blade for 15.5 kg/s, 14800 RPM, 276.5 KW power with a tip speed 167.7 m/s. The aerodynamic design and blade profiling has been carried out using CFD software. The research starts with design of the high pressure ratio compressor blade sections which yield a single stage pressure rise up to 1.21. Further the design is optimized for minimum total pressure loss. Prototype blade cascades were tested in low speed wind tunnel for performance parameters. Resulting data from experiment s compared with the numerical analysis.

***Index Terms* - Axial flow compressor, aerodynamic design, CFD modeling, experimental validation, wind tunnel cascade test**

I. INTRODUCTION

The overall gas turbine engine performance depends on the components' performance like compressor, compressor, combustor and turbine. Among these components the compressor plays a vital role. Hence it is required to know the performance and aerodynamic behaviour of the compressor before it is integrated into the engine. The prime requirement of Gas turbine engine manufacturers is efficiency and power to weight ratio. It is possible in two ways, increase the maximum combustion temperature and increase maximum pressure in compressor. The former is limited to the turbine inlet temperature and turbine blade material. The later can be achieved by running the compressor at higher speed. It results in the either high subsonic or transonic flow. But the sonic flow creates high losses in the cascade because of the formation of shock waves. Hence the other way to achieve an efficient compressor is by improving the compressor blade design. The current trend in compressors is to design an optimized blade with minimal pressure loss and higher pressure ratio. The present work carries out the optimization of the blade profile for the compressor cascade at high subsonic inlet flow conditions. An attempt has been made to design and configure a single stage axial flow compressor to a gas turbine engine producing 276.5 KW power output used for power generation.

II. RESEARCH METHODOLOGY

The aerodynamic design of axial flow compressor is carried out by selecting the optimum engine cycle parameters like cycle pressure ratio, RPM, Compressor efficiency, turbine efficiency and turbine entry temperature. Based on the compressor pressure ratio from [4] and mass flow rate calculated from cycle analysis, the aerodynamic design of compressor is carried out to get overall dimensions of the compressor and flow angles at inlet and outlet of the stage. The required flow variation area, the blade height was estimated by considering radial equilibrium and exponential method of velocity distribution. After calculating the overall dimension, and assuming solidity and aspect ratio, number of blades is calculated and shaft diameter is calculated. Optimisation of axial flow compressor design was a very tedious task as a small variation in one parameter will have a considerable change in compressor design, also to choose the optimum values is an art, so AXTREAM provides a good option to this problem and design can be optimised in no time by redesigning it as per requirement. The results obtained through it shows very good agreement for both design and off design conditions i.e. getting enough stall and choke margin with required pressure ratio at given mass flow and RPM. Scaled prototypes of blades are cascade tested in low speed wind tunnel. Pressure gradient and flow coefficient values from experiment are in agreement with software data thus validating the optimised design.

2.1 Design Specification and Assumptions for Stage Design

Based on the problem statement defined from cycle analysis, design specifications for single stage axial flow compressor are

Mass Flow rate at Atmospheric condition	15.5 kg/sec
Rotor speed	14800 RPM
Inlet total Temperature	298 K
Inlet total Pressure	101325 N/m2

2.2 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.

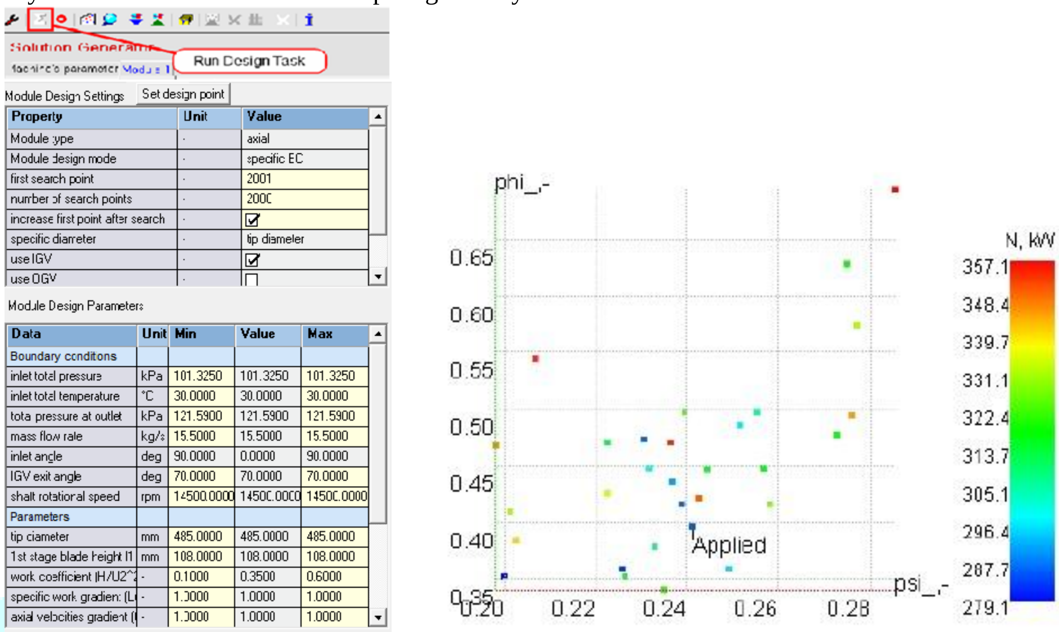


Figure 1: Module design Parameter and Design Space generator with filtered solutions for an axial flow compressor

Preliminary design starts from specification of technical requirement and setting up design task and compressor conceptual layout that includes: Inlet and outlet boundary conditions (inlet pressure, temperature, pressure raise ratio etc); Conceptual design and sizing layout i.e. quantity of modules (group of stages) inside compressor, number of stages in each group, meridional and axial sizes limitations, work coefficient; 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. Next machine parameters selected are as Inlet and outlet condition type and values; Design criterion (power and choice of efficiencies) and Number of modules.

A solution generator generated the possible solution in the design space explorer which is later filtered based on design criterion of power and work efficiency as well as subsonic Mach number. The filtered solutions are validated to provide better coincidence of results to design conditions.

2.3 Performances Map Generation for Design Point in PD MAP

PDMAP helps PD MAP is the tool to evaluate the created design performances on speed line by calculating compressor curves that are necessary for initial compressor characteristics assessment. At this stage of design process, optimum design solution is tested for the coincidence of the speed line with design point and gas dynamic stability range is evaluated by redefining the pressure ratio.

2.4 Post-Design of Compressor.

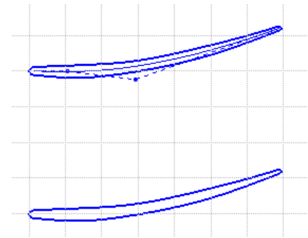
In the post design process, applied design is subjected to compressor flow path editing, adjustment of specific diameters of the whole flow path and adjustment of number of blades; chords and aspect ratio (blade height/chord). It tries to keep solidity (relative pitch) near the value, selected by preliminary design.

2.5 1D/2D Streamline Calculation

Two-dimensional profile cascade losses arise primarily from the growth of the boundary layer on the suction and pressure side of the blade [35]. The 1D and 2D calculation will show that the various flow parameters i.e. static pressure distribution in compressor, total pressure and absolute pressure distribution, meridonal velocity and mach number.

2.6 3D Blade Design and Profiling

The next step is to perform profiling on plane profiles section to obtained optimum flow characteristics and pressure distributions. On the next step 3D blade design, stacking and shaping are performed and complete geometry which is ready to export is obtained. In this section we adjust the curve of blade make the curvature of blade smooth to get the optimum result. This task is performed by blade parameter editing command i.e. Edit mode. The fig. 2 will show the blade editing and fig. 3 shows the smooth curve of blade.



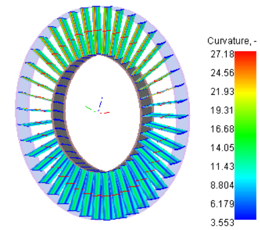


Figure 2: Blade Profiling Figure 3: Blade Curvature Smoothness

2.7 OFF-DESIGN PERFORMANCES CALCULATIONS WITH AxMAP

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. It is also used to predict, at which blade row the 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. The applied design is tested for stall formation at two selected speed lines and is checked for critical diffusion factor.

2.8 Experimental set up

To validate numerical results, wind tunnel experimental test has been carried out using blade cascade as shown in figure 4. Mach number, Pressure gradient and flow coefficient values from experiment are compared with software data. A variable speed axial flow fan and tubular duct occupy 0.6 m length of the total length of the tunnel. Air velocity may be varied turning rheostat of the drive AC motor.

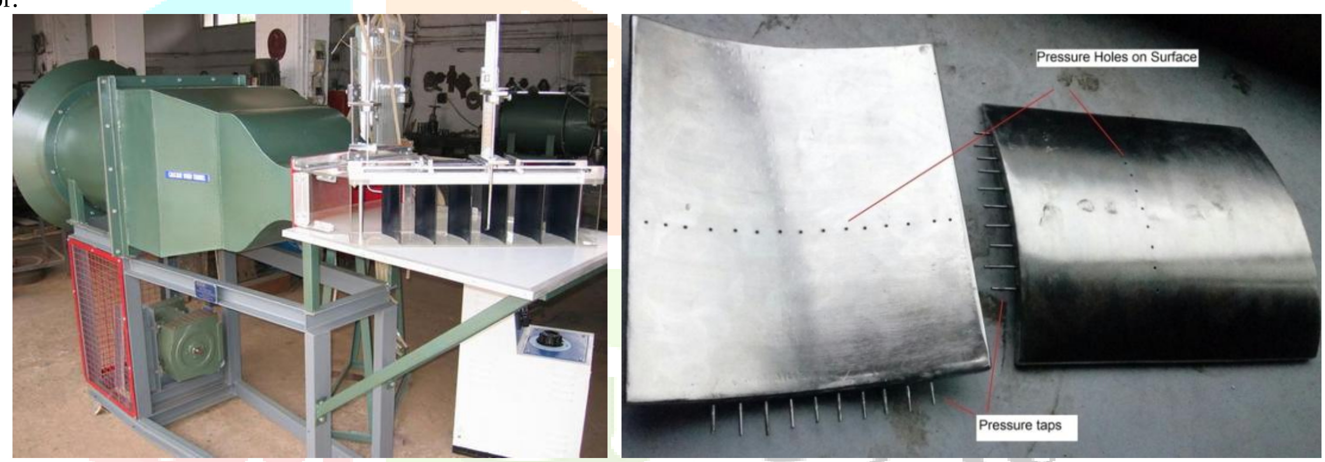


Figure 4: Experimental setup and blade profiles

Cascade test section has rectangular cross section of 0.5m x 0.15m and 0.75m length. It also has provision for changing the angle of incidence.

III. RESULTS AND DISCUSSIONS

The axial flow compressor redesign and optimization is carried out using the AXSTREAM according to the procedure discussed before and the results are as under. The Finalized Data after redesign in preliminary design and space explorer is as under

Aerodynamic design of an axial flow compressor with

Mass flow 15.5 Kg/s.

Stage pressure ratio = 1.21

Rotational speed = 14800 rpm

The use of inlet guide vane improves the efficiency by almost 10%. The average peak Mach No. Is 0.7690. This indicates it is operating in subsonic range. The performance characteristic curve obtained in AXMAP is shown in Fig.5 indicates the compressor is matching the performance i. e. is delivering the given mass of air at designed outlet pressure; also the compressor has sufficiently wide range for stall and choke. The choking range at designed RPM is 1.2 bar and stalling range is 1.7 bar.

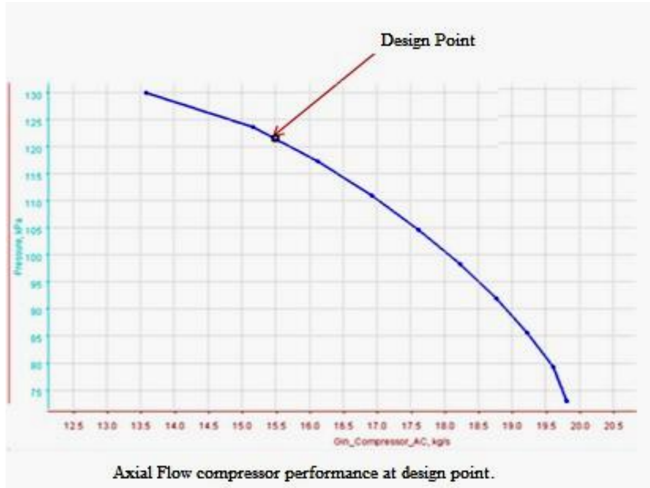


Figure 5: Performance curve of Compressor

Post design shows velocity triangle and HS Diagram for respective section as shown in figure 6. Also it reveals the same for sections of machine which indicates proper flow angles i.e. no excessive turning of blades.

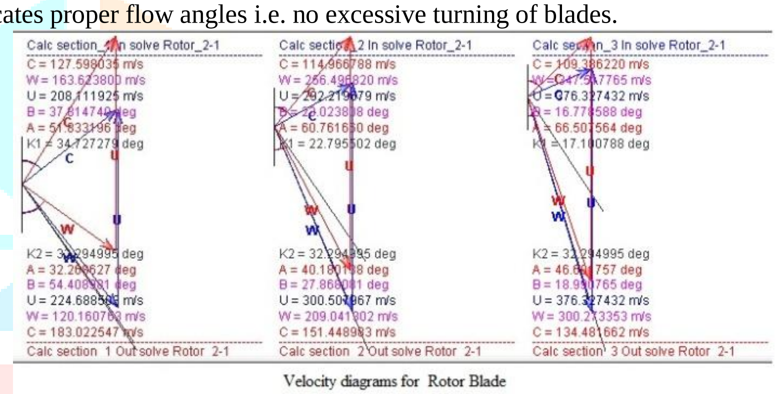


Figure 6: Velocity diagram for Compressor blades

After running the calculations for the post design the machine dimensions are obtained like the radius at each section from hub to tip, the dimensions for machine including shaft.

Fig. 7 machine dimensions of axial flow Compressor

After running 1D and 2D calculations the parameters obtained are shown in Figure 8. The variation of Parameters such as absolute Mach number, relative Mach Number and Total Pressure are given in a very good agreement between design point and computation results. The results indicate that maximum pressure, absolute maximum pressure, maximum maridonal velocity, absolute Mach number and relative Mach number are at 158.6 kPa, 195.1 kPa 162.7 m/s, 0.41 and 1.081.

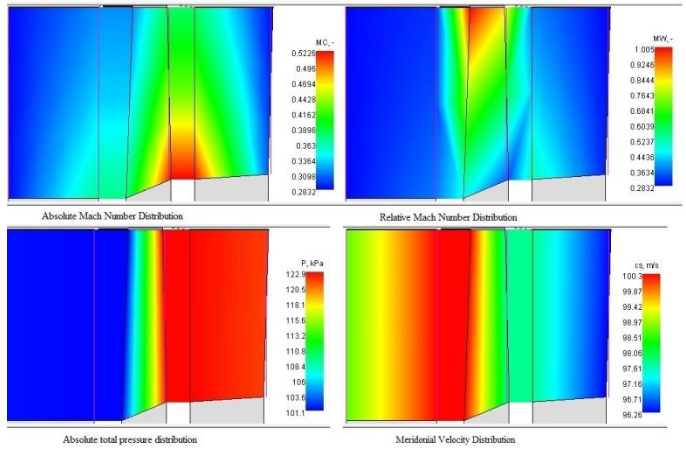


Figure 8: Results of flow analysis of axial flow Compressor

3D structural and modal analysis is carried out 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. Modal analysis will give the frequency at various modes shown in figure 9. The stress is maximum at leading edge and tailing edge.

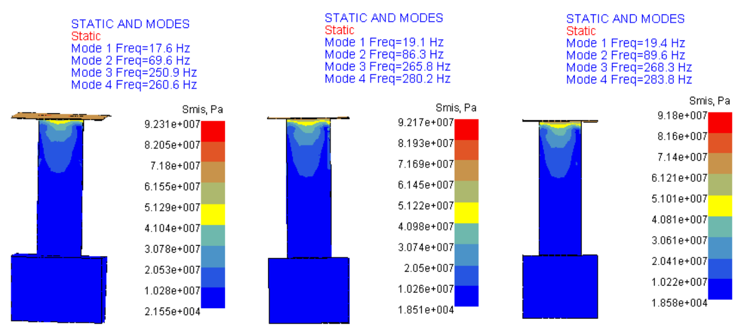


Figure 9: Results of 3D Structural and modal analysis

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 Figure 10.

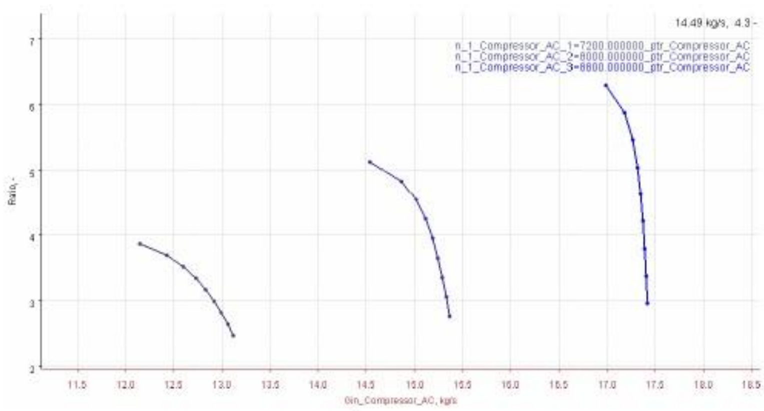


Figure 10: Off design performance of the axial flow compressor

Using analytical and numerical analysis the results for various properties are compared as follow

Table 1: Analytical results and numerical results data

Property	**Analytical Results**	**Numerical Results**
Static pressure at outlet, kPa	113.4268	114.4
total pressure at outlet, kPa	121.6005	121.77
static temperature at outlet, °C	47.6447	48.05

Power, kW	278.25	278.91
Total static pressure ratio	1.1194	1.11
diffusion factor (by NASA)	0.2882	0.267
diffusion factor by de Haller (w2/w1)	0.8230	0.8405
Average flow coefficient (C2s/U2)	0.3446	0.33
total pressure rise, kPa	20.2755	20.45
static pressure rise, kPa	12.1018	12.07
total pressure loss factor	0.0213	0.0216
Mach number	0.4180	0.4151

The above comparison made between the numerical and analytical study shows that the pressure rise are nearly closed to each other, it also indicate that the slightly change in diffusion factor by NASA and diffusion factor by De Haller number.

Further wind tunnel cascade experiment results are tabulated along with analytical results and numerical results obtained from AxSTREAM software.

TABLE 2: Comparison of analytical, numerical and Experimental Data

Property	**Analytical Results**	**Numerical Results**	**Experimental data**
Inlet Total Pressure, kPa	101.3	101.3	101.2
Inlet Total Temperature, K	298	298.2	298
Inlet Mass flow Rate, kg/s	15.5	15.5	15.4
No. of Blades	42	42	42
RPM	14800	14800	14788
Outlet Total Pressure, kPa	121.6005	121.77	120.0
Outlet static temperature, K	321.5	321.5	320.2
Mach No.	0.4180	0.4151	0.40

When total loss is plotted against incidence angle, as shown in Figure11, it is observed that the values increases with an increase in incidence angle towards positive side and the experimental values are slightly on upper side of calculated values. It shows that the compressor blades show required off design performance to best possible degree.

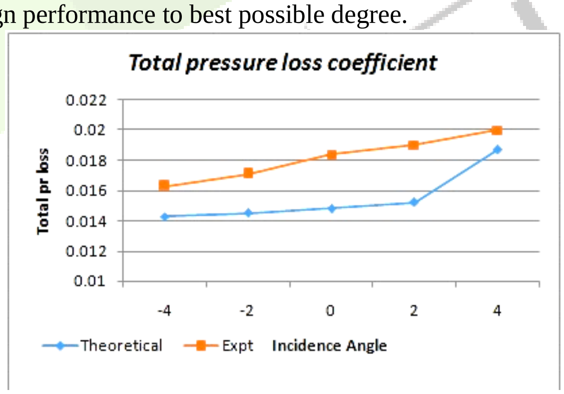


Figure 11: Total pressure loss coefficient against angle of incidence

Figure 12 shows the Mach number distribution obtained from experiment is compared against the numerical values from AxSTREAM data.

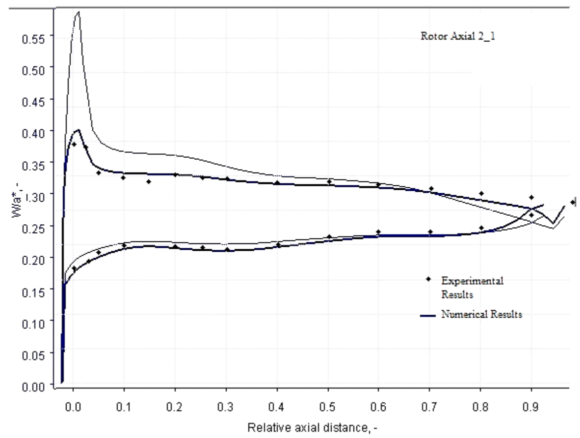


Figure 12: Total pressure loss coefficient against angle of incidence

IV. CONCLUSION

The single stage axial flow compressor is designed for the constant tip diameter of the compressor rotor blade for mass flow rate 14.4 kg/s, RPM 14800, a single stage pressure ratio 1.21 with a tip speed 167.7 m/s and 276.5 KW power. The aerodynamic design is optimized using blade profiling in CFD software for minimum total pressure loss. Cascade test is carried out in wind tunnel. Results from experiment match with the numerical results, thus confirm the validity the optimized design.

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