Five-Stage Axial Flow Compressor for Gas Turbine

Khema Theint
Department of Mechanical Engineering, Technological University (Kyaukse)
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Abstract- The goal of this paper is to calculate the blade design of axial flow compressor. Main objective of the compressor usage is to compress the fluid and to deliver higher pressure than its original pressure. So, the stagnation pressure ratio and overall pressure ratio are calculated in this paper. Blade mean diameter is 0.295 m for all five stages. The number of blades for each stage calculated in this paper is 82 blades for first stage, 90 blades for second stage, 117 blades for third stage, 175 blades for fourth stage and 307 blades for fifth stage. In this study, inlet flow rate is 20451 CFM, outlet flow is 2811.427 CFM, compressor horsepower is 1060 hp, polytropic head is 255.649 kNm/kg and efficiency of compressor is 91.83%. And then, the general performance curves of axial flow compressor are described based on the inlet flow rate, pressure ratio and head. When these performance curves are compared with the original performance curve of axial flow compressor, the curves are nearly similar. So, the design calculation results of axial flow compressor are satisfied.

Index Terms- gas turbine, rotor, stator, blade design, axial compressor

I. Introduction

Axial compressors are compressors in which the fluid flows mainly parallel to the axis of rotation. An axial compressor comprises a number of stages as determined by the required overall pressure rise. Each stage includes a rotating row of blades (rotor) followed by a stationary row of blades or vanes (stator). The rotor blades impart momentum to the fluid thus increasing the total energy of the flow and propelling the fluid along the axis of the machine. The stator vanes convert much of the fluid momentum into pressure energy so that a rise in the static pressure across the stage occurs whilst the mean axial velocity of the flow through the stage is approximately constant. The angles of the blades and vanes relative to the direction of flow are critical to the pressure rise and operating efficiency of a stage.

II. Design Calculation of Five-Stage Axial Flow Compressor for Gas Turbine

A. Design Calculation Of Blade Design For Axial Flow Compressor

An axial flow compressor used in gas turbine engine has constant axial velocity throughout the compressor of 152 m/s, blade mean velocity of 162 m/s and it is delivered 10.5 kg of air per second at a rotational speed of 10500 rpm. Reaction ratio is 50 % for each stage and the work done factor is 0.92. Stage efficiency and polytropic efficiency is 84 % and 87 %. Stagnation temperature rise for each stage is 15°K. Inlet stagnation temperature and pressure is 288°K and 1 bar. Blade aspect ratio and pitch-chord ratio are 3 and 0.5. In this research, the design data of axial flow compressor used in gas turbine engine is picked up from the Ta Dar Oo airway in Myanmar.

Axial flow compressor has the following known data;

Constant axial flow velocity, C_a = 152 m/s
Blade mean velocity, U_m = 162 m/s
Mass flow rate, m = 10.5 kg/s
Rotational speed, N = 10500 rpm
Reaction ratio, R = 50 %
Work done factor, λ = 0.92
Inlet stagnation temperature, T_{01} = 288°K
Inlet stagnation pressure, P_{01} = 1 bar
Stagnation temperature rise, ΔT_{0s} = 15°K
Stage efficiency, η_s = 84 %
Polytropic efficiency, η_p = 87 %
Blade aspect ratio, AR = 3
Pitch-chord ratio, s/c = 0.5
Assume properties of air, γ = 1 , C_p = 1005 kJ/kg°K , MW = 28.96 , R = 287 J/kg°K

(i) Determination of the Blade Mean Diameter, $U_m = \frac{\pi \times D_m \times N}{60}$

(ii) Calculation of Stagnation Pressure Ratio, $R_s = \left[1+\frac{\eta_s \times \Delta T_{0s}}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$

(iii) Calculation of the Air and Blade Angles for Rotor, $\Lambda = \frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2)$

(iv) Calculation of the Rotor Inlet Properties,

Absolute Velocity , $\cos \alpha_1 = \frac{C_a}{C_1}$,Whirl Velocity, $\sin \alpha_1 = \frac{C_{w1}}{C_1}$ Relative Velocity, $\cos \beta_1 = \frac{C_a}{V_1}$

(v) Calculation for First Stage

Number of blades, blade hub and blade tip diameters for first stage can be calculated by $T_{02} = T_{01} + \Delta T_{0s}$.

Outlet stagnation pressure can be calculated from stagnation pressure ratio equation, $R_s = \frac{P_{02}}{P_{01}}$

Outlet static temperature, $T_2 = T_{02} - \frac{C_2^2}{2C_p}$

Outlet static pressure , $\frac{P_2}{P_{02}} = \left[\frac{T_2}{T_{02}}\right]^{\frac{\gamma}{\gamma-1}}$

Inlet static temperature , $T_1 = T_{01} - \frac{C_1^{\ 2}}{2C_p}$

Inlet static pressure, $\frac{P_1}{P_{01}} = \left[\frac{T_1}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$

Air Density, $\rho_1 = \frac{P_1}{RT_1}$

mass, $m = \rho_1 \times A_1 \times C_a$

Blade Height, $A_1 = \pi \times D_m \times h_1$

Number of Blades, $z = \frac{\pi \times D_m}{s}$

Tip and Hub Diameter, $D_t = D_m + h_1$, $D_h = D_m - h_1$

(vi) Calculation for Second, Third, Fourth and Fifth Stage

Outlet stagnation temperature and pressure at the previous stage is inlet stagnation temperature and pressure for the next stage. So, stagnation temperature, stagnation pressure, static temperature, static pressure, air density, flow area, blade height, blade chord, blade thickness, blade pitch, number of blades, blade hub and blade tip diameters for the remaining stages of compressor rotor can be described by the following result table.

Table. Result Table of Five-Stage Axial Flow Compressor

Stage	1	2	3	4	5
T_{01} (°K)	288	303	318	333	348
P_{01} (bar)	1	1.162	1.569	2.462	4.489
R_s	1.162	1.35	1.569	1.823	2.118
T_{02} (°K)	303	318	333	348	363
P_{02} (bar)	1.162	1.569	2.462	4.489	9.507
T_1 (°K)	276.05	291.05	306.05	321.05	336.05
P_1 (bar)	0.862	1.009	1.372	2.166	3.972
T_2 (°K)	282.91	297.91	312.91	327.91	342.91
P_2 (bar)	0.914	1.248	1.98	3.645	7.789
ρ_1 (kg/m^3)	1.088	1.208	1.562	2.351	4.118
A_1 (m^2)	0.063	0.0571	0.044	0.0294	0.0167
h_1(m)	0.068	0.062	0.048	0.032	0.018
c_1(m)	0.022	0.021	0.016	0.0105	0.006
t_1 (m)	0.00022	0.00021	0.00016	0.00011	0.00006
s_1 (m)	0.011	0.0102	0.008	0.0052	0.003
n (blades)	82	90	117	175	307
D_t (m)	0.363	0.357	0.343	0.327	0.313
D_h (m)	0.227	0.233	0.247	0.263	0.277

B. Calculation of Power of Axial Flow Compressor

(i)To calculate the compressor power,

the work done of compressor , $W = C_p \times \Delta T_{overall} = C_p \times (T_{02} - T_{01}) = 75.375$ kJ/kg

Compressor power , Power $= m \times W = 10.5$ kg/s $\times$ 75.375 kJ/kg = 1060 hp

(ii)Calculation of Polytropic Head

Assume Z = 1, MW = 28.96

Specific gas constant is $R = \frac{8314}{MW} = 287$ J/kg°K

(iii)Static temperature at compressor outlet can be calculated by $T_2 = 363 - \frac{200.95^2}{2 \times 1005} = 342.9$°K

(iv)Outlet static pressure can be calculated from $\frac{P_2}{P_{02}} = \left[\frac{T_2}{T_{02}}\right]^{\frac{\gamma}{\gamma-1}} = 7.789$ bar

(v)Pressure ratio across the compressor is $r_p = \frac{P_2}{P_1} = 9.036$

(vi)Polytropic head can be calculated by $H_p = Z \times R \times T_1 \times \frac{n}{n-1}\left[(r_p)^{\frac{n-1}{n}} - 1\right] = 255.649$ kNm/kg

C. Calculation of Inlet and Outlet Mach number

(i)Inlet Mach number is calculated by $M_1 = \frac{V_1}{\sqrt{\gamma \times R \times T_1}} = 0.6$

(ii)Outlet Mach number is calculated by $M_2 = \frac{C_2}{\sqrt{\gamma \times R \times T_2}} = 0.54$

(iii)Calculation of Inlet and Outlet Flow

Inlet flow , $Q_1 = \frac{m \times Z \times R \times T_1}{P_1} = 9.65\ m^3/s = \frac{9.65\ m^3}{(1\ m)^3} \times \frac{(3.281\ ft)^3}{(1\ m)^3} \times \frac{60\ s}{1\ min} = 20451$ CFM

Outlet flow , $Q_2 = \frac{m \times Z \times R \times T_2}{P_2} = 1.326\ m^3/s = \frac{1.326\ m^3}{(1\ m)^3} \times \frac{(3.281\ ft)^3}{(1\ m)^3} \times \frac{60\ s}{1\ min} = 2811.427$ CFM

D. Efficiency of Axial Flow Compressor

To calculate the efficiency of compressor, ideal stagnation temperature at compressor outlet can be determined by using following equation, $\frac{T_{02}'}{T_{01}} = \left[\frac{P_{02}}{P_{01}}\right]^{\frac{\gamma - 1}{\gamma}}$

$T_{02}' = [2.118]^{\frac{1.4 - 1}{1.4}} \times 288 = 356.873$°K

Efficiency of compressor , $\eta_c = \frac{T_{02}' - T_{01}}{T_{02} - T_{01}} = \frac{356.873 - 288}{363 - 288} \times 100\% = 91.83\%$

E. Classification of Compressor Types

Compressors can be classified based on the inlet flow and pressure ratio across the compressor.

Type of compressor is multi-stage axial flow compressor from the value of pressure ratio and inlet flow. Thus, the design of axial flow compressor is satisfied.

F. Performance Curves for Axial Flow Compressor

Performance curve is important for the design of compressor and this performance curve can be checked whether this design is satisfied or not satisfied. Figure .1 shows the performance curve of axial flow compressor based on the inlet flow rate, Q and pressure ratio and Figure .2 provides the performance curve using the value of inlet flow rate, Q and head. The design performance curves are nearly similar to the original performance curve of axial flow compressor. So, the design calculations of axial flow compressor are satisfied.

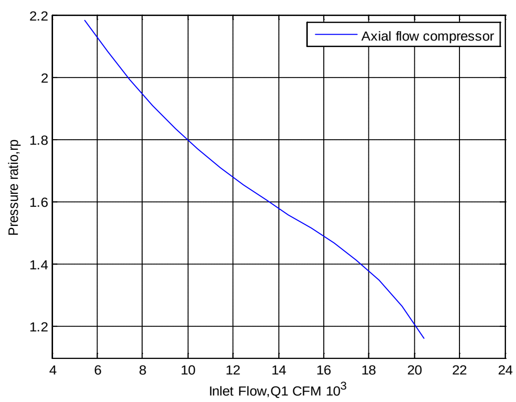


Figure.1. Performance Curve for Axial Flow Compressor; r_p and Q_1

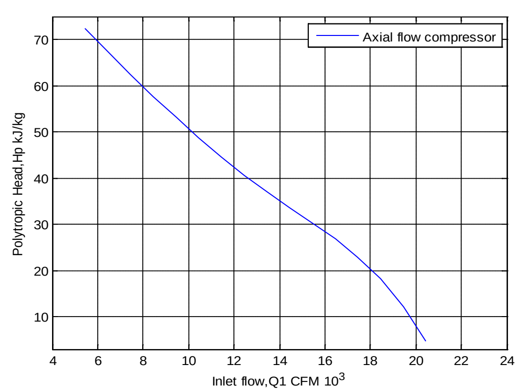


Figure.2. Performance Curve for Axial Flow Compressor; H_p and Q_1

III. Conclusion

This paper is attempted to design multi-stage axial flow compressor for gas turbine engine. The design of compressor calculated in this paper is blade mean diameter of 0.295 m for all five stages. Number of blades for the first stage rotor is 82 blades, the second stage rotor is 90 blades, the third stage rotor is 117 blades, the fourth stage rotor is 175 blades and 307 blades for the fifth stage rotor. Material selection for the rotor blade is steel. Rotor air inlet angle α_1 is 11.3° and rotor air outlet α_2 is 40.85°. Rotor blade inlet angle β_1 is equal to rotor air outlet angle α_2 and rotor blade outlet angle β_2 is equal to rotor air inlet angle α_1 since the reaction ratio for this compressor is 50%. Inlet absolute velocity, C_1 is 155 m/s, inlet whirl velocity, C_{w1} is 30.37 m/s and inlet relative velocity, V_1 is 200.95 m/s. Inlet relative Mach number, M_1 is 0.6. Outlet absolute velocity, C_2 is 200.95 m/s, outlet whirl velocity, C_{w2} is 131.43 m/s and outlet relative velocity, V_2 is 155 m/s. Outlet Mach number, M_2 is 0.54. Inlet and outlet flow is 20451 CFM and 2811.427 CFM. Polytropic head is 255.649 kNm/kg. Compressor horsepower is 1060 hp and the efficiency of compressor is 91.83%.

Appendix

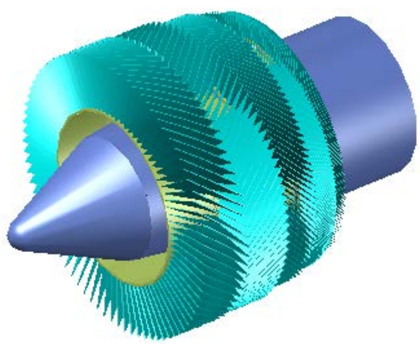
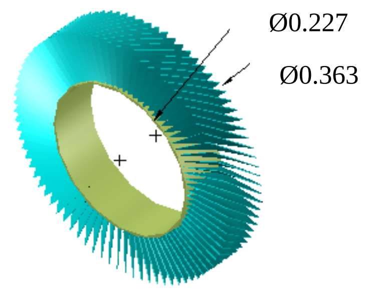


Figure A.1.Section View of Axial Flow Compressor Rotor



Figurea.A.2. Section View of First Stage Rotor

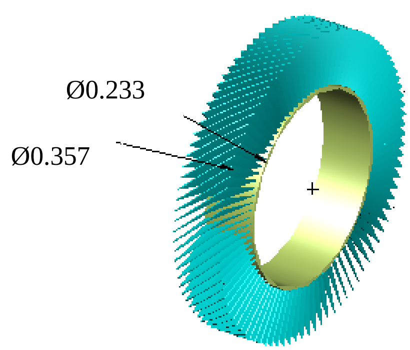


Figure .A.3. Section View of Second Stage Rotor

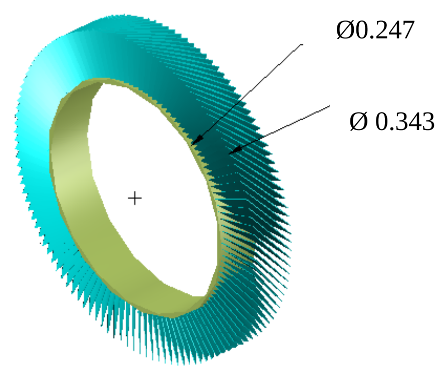


Figure .A.4. Section View of Third Stage Rotor

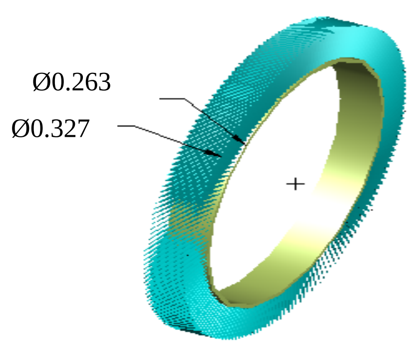


Figure .A.5. View of Fourth Stage Rotor

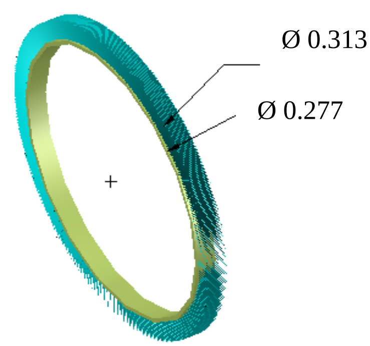


Figure .A.6. View of Fifthth Stage Rotor

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AUTHOR

Author – Khema Theint, Lecturer, Technological University (Kyaukse) and khematheint@gmail.com.