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Load Calculation & Selection of Bearing for Low Pressure Compressor (LPC) For Al -31FP Engine

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ABSTRACT

This paper presents based on the inputs obtained from a working engine AL-31FP. The AL-31FP Engine is used to power the Su-30 MKI aircraft. It is a twin spool afterburning turbofan engine with mixing main flow and by-pass flow downstream turbine, with thrust vectoring nozzle. Its compressor is an axial flow compressor with a pressure ratio of 23 and is made by integrating the low pressure compressor and the high pressure compressor. The low pressure compressor has 4 stages with one stage of inlet guide vanes which has a pressure ratio of 3.5. The high pressure compressor has 9 stages with 3 stages of variable stator vanes which has a pressure ratio of 6.6. Its engine consists of an annular combustion chamber with 3 igniters and 28 number of duplex fuel nozzles.

There are six bearings used in AL-31 FP in main transmission line. For low-pressure compressor two bearings are used i.e. front support roller bearing and rear support ball bearing. There are various forces acting on bearings such as radial forces, axial forces. Therefore estimation of these forces is necessary. From these forces equivalent bearing load can be calculated. After taking suitable bearing life and load factor dynamic load carrying capacity can be found out. Finally after knowing dynamic load carrying capacity and bore dimensions suitable bearing can be selected from the catalogue.

Key words- AL-31FP, 31-Series, FP-Thrust vector, TBO-Time before overhaul, dynamic loads.

1 INTRODUCTION

Al-31 FP(Arif & Lulca 31series Fersa Thrust Vector) engine is afterburning turbofan engine with mixing of bypass and main ducts flows downstream the turbine with thrust vectoring nozzle.

Compressor is an axial, 2 spools and 13 stage compressor. The compressor consists of-

a. 4 stage low-pressure compressor (LPC) with variable inlet guide vane(IGV)
b. 9 stage high pressure compressor (HPC) with 3 variable stator vanes (Inlet and first 2 stages guide vanes)
c. Intermediate casing

Combustion chamber is annular Engine turbine is an axial, 2 stage turbine. It consists of –

a. Single stage high pressure turbine (HPT) with cooled disc

b. Single stage low pressure turbine (LPT) with air cooled disc
c. Turbine support

Afterburner with flows mixing at the afterburner transition section inlet.Thrust vectoring nozzle

- It consists of tilting unit and jet nozzles.

Fig 1-High purpolsion with low thrust

fig 2-low purpolsion with high thrust

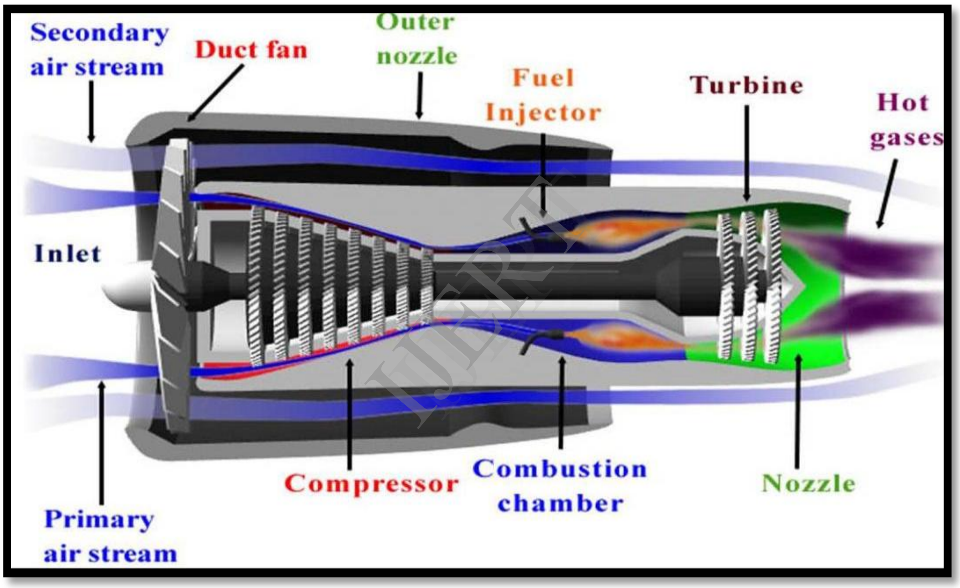


Fig 3: Turbofan Engines

A turbofan engine may be considered a cross between turbojet engines& turboprop engines. In this engine air from the fan section of the forward blades is carried outside to the rear of the engines through ducting. The effect of turbofan engine design is to greatly increase the power-weight ratio of the engine& to improve the thrust specific fuel consumption. Turbofan engine may be high-by pass or low bypass engines. The ratio of the amount of air that by –passes the core of the engine to the amount of air that passes through the core is called the by pass ratio. Many different types of turbofan engines are in use & can be found on air craft from small business jets to large transport type aircraft

The rotor blades increase the air velocity. When air velocity increases, the ram pressure of air passing through a rotor stage also increases. This increase in velocity and pressure is somewhat but not entirely nullified by diffusion. When air is forced past the thick sections of the rotor blades static pressure also increases. The larger area at the rear of the blades (due to its airfoil shape) acts as a diffuser

Spang and Brown[1999][1] were reviewed the basics of controlling an engine while satisfying numerous constraints. In the published paper by Maggiore[2003][2] the concept so developed were applied to estimator design for jet engine thrust, stall margins, and an unmeasurable state. Boyce [2006][3] focuses on bearings and seals. The bearings in gas and steam turbines provide support and positioning for the rotating components. Montazeri-Gh et al.[2012][4] presented an actuator-based hardware-in-the-loop (HIL) simulation for testing of a jet engine fuel control unit (FCU). Mlynarek and Van Orden [2012][5] were demonstrated that the disturbance of asbestos-containing gaskets. H.K.D.H. Bhadeshia [2012][6] was given a report on steels used in the manufacture of some of the most technologically important engineering components, the rolling bearings. The jet engine maintenance process is complex, expensive and time-consuming. It often requires engine disassembly or baroscopic examinations. In order to accelerate the process and reduce the down time of an engine Adamczuk and Seume [2013][7] . Progress in the design and structural analysis of commercial jet engine fan blades is reviewed and presented. The article published by Amoo [2013][8] was motivated by the key role fan blades play in the performance of advanced gas turbine jet engines.

2.1. COMPRESSOR DETAIL

The compressor is axial, 2-spool, 13 stages is made of titanium & steel alloys.It consists of 4 stages LPC with adjustable flaps of one inlet guide vane assembly and 9 stages of HP stator with 3 adjustable guide vane units (inlet and first two stages) and the intermediate casing.

Total Number of blades:2443
In which Rotor blades: 981
Stator blades: 1462

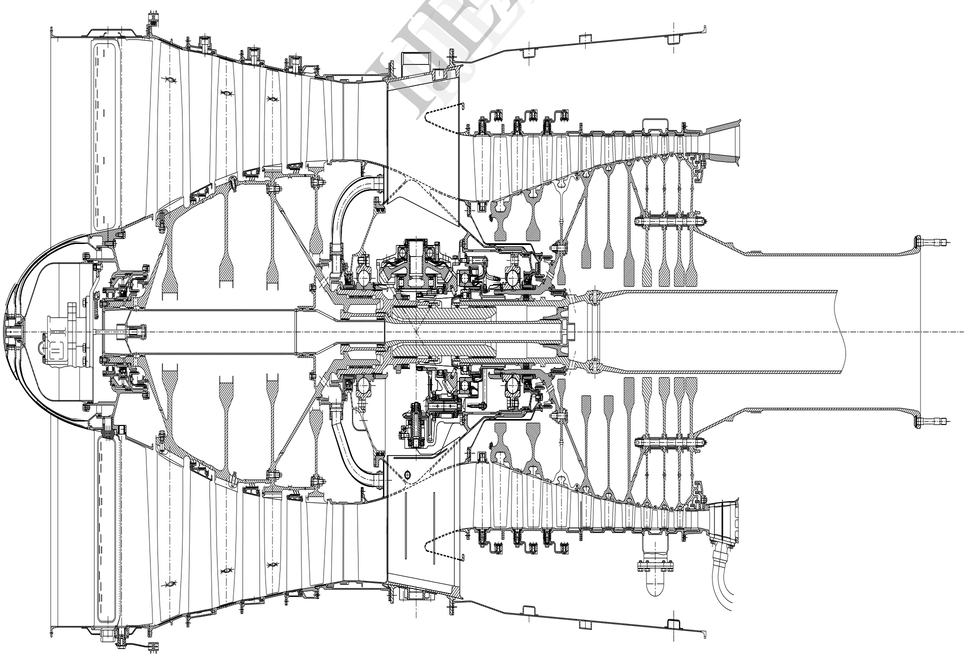


Fig 4: AL31FP ENGINES

The Compressor comprises:

- 4 Stage Low Pressure Compressor (FAN) with Inlet Guide Vanes

- 9 Stage High Pressure Compressor (GAS GENERATOR) with Three Swiveling Guide Vanes Intermediate Casing.

Assumptions :

- Axial velocity is constant in LP compressor
- Polytropic efficiency of compressor = 0.87
- Polytropic efficiency of LPC = 0.89
- Polytropic efficiency of 1st 2nd 3rd & 4th stage = 0.9
- Degree of reaction of 2nd stage = 0.65
- Degree of reaction of 3rd & 4th stage = 0.50
- Pressure of air at the front side of LPC disc is as same as that of after 4th stage of LPC
- Pressure of air at the rear side of LPC disc is as same as that of after 4th stage of LPC
- Combustion is constant pressure process
- expansion ratio = 7
- polytropic efficiency of LPT stage = 0.9
- Area before LPT disc is pressure vessel having uniform thickness
- Average life of ball & roller bearings = 3000 hrs
- Dynamic load carrying capacity of existing roller bearing C= 75 k N

2.2 COMPRESSOR CHARACTERISTIC

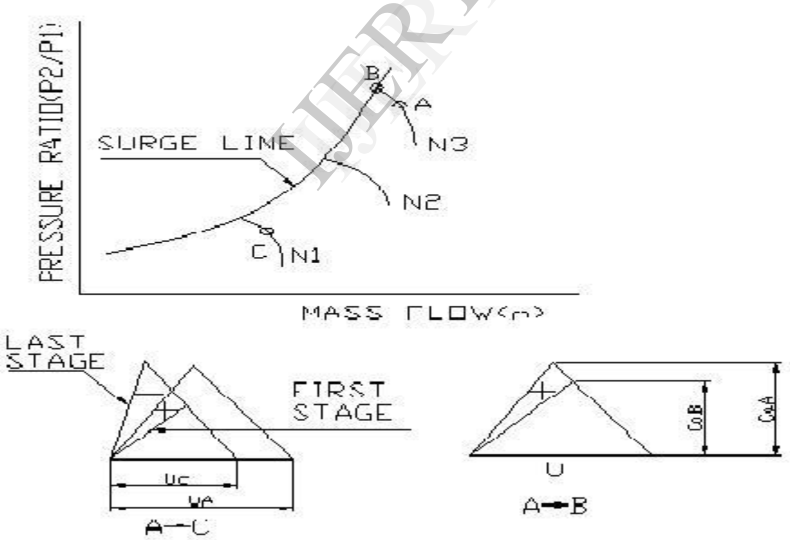


Fig: compressor p-v diagram

Moving from A-B, Pressure increases & Density. But the mass flow decreases slightly. It results in increase in axial velocity & increase in incidence, and stalling will happen in last stage. Speed reduced from A-C, Mass flow falls off more rapidly than the speed, and the effect is to decrease the axial velocity at inlet and cause the incidence on first stage blade to increase.

3.1 FORCES ACTING ON LP COMPRESSOR FRONT & REAR SUPPORT BEARINGS

There are various forces acting on LPC bearings i.e. front support roller bearing & rear support ball bearing. These forces can be divided into 2 types radial forces and axial forces.

A) Radial forces
   1. Due to dynamic unbalance state of rotor
   2. Due to gyroscopic effect
   3. Due to weight of rotor

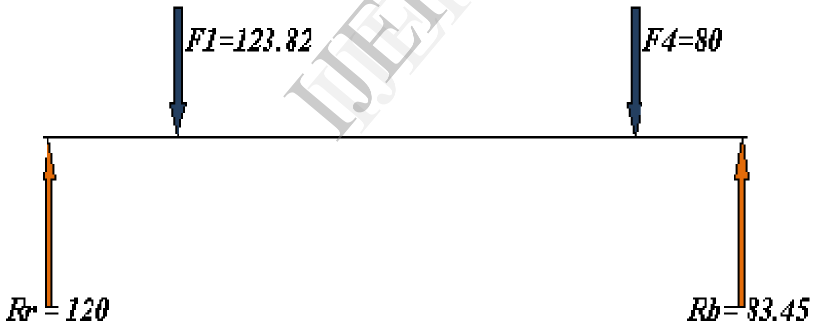
B) Axial forces
   1. Axial force due to action of gases on LPC rotor
   2. Axial force due to action of gases on LPT rotor

3.2 FORCE ACTING DUE TO UNBALANCE STATE OF ROTOR

Centrifugal force = m r ω^2

Centrifugal force on 1st stage =$(8.86 \times 10^{-3} \times 10^{-2} \times 1151.92^2) = 123.82$ N

Centrifugal force on 4th stage = $5.98\times 10^{-3} \times 10^{-2} \times 1151.92^2$ =80 N



3.3 FORCE ACTING DUE TO GYROSCOPIC EFFECT

Inertial forces and moment appear in the engine due to change in value or direction of speed of flight of the aircraft on which the engine is mounted. These forces are transmitted to the body through the bearing in the form of radial forces. The direction of these forces changes in time with change of angle of rotation of the rotor. This causes appearance of gyroscopic moment of the rotor and inertial overloads.

The gyroscopic moment is given by M= J Ω ω sin α

Max. Velocity of SU-30 = 2290 km/hr = 636.11 m/s

& Max k = 9

$\therefore \Omega = 9\times9.8/636.11$

$\therefore \Omega = 0.1387$ rad/s

Mass moment of inertia of rotor = 9 kg-m^2

N = 11000 rpm

$\therefore$ ω = 1151.92 rad/s

Taking α = 75

The gyroscopic moment= J Ω ω sin (75)= Max. Velocity of SU-30 = 2290 km/hr
= 636.11 m/s

& Max k = 9

$\therefore \Omega = 9\times9.8/636.11$

$\therefore \Omega = 0.1387$ rad/s

Mass moment of inertia of rotor = 9 kg-m^2

N = 11000 rpm

$\therefore$ ω = 1151.92 rad/s

Taking α = 75

The gyroscopic moment= J Ω ω sin (75) =1388.9 N-m

$\therefore$ Force acting due to gyroscopic effect = 1437.94/0.480=2.9 kN

3.4 STATIC FORCE ACTING DUE TO WEIGHT OF ROTOR

In static condition force due to weight of rotor is acting on bearings Considering mass of discs and rotor blades

Mass of 1st stage disc =12.743 kg = 124.88 N

Mass of 1st stage blades = 0.28 kg (37) = 10.36 N

$\therefore$ Mass of 1st stage disc & blades = (124.88+10.36) = 135.24 N

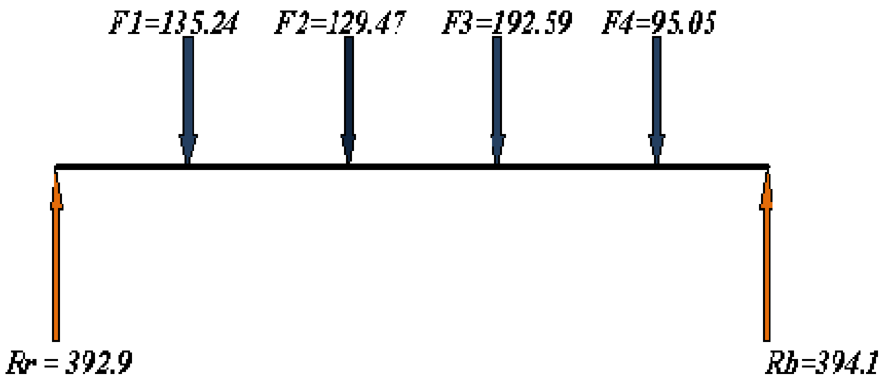
$\therefore$ Mass of 2nd stage disc & blades = (122.5+6.975) = 129.475 N

$\therefore$ Mass of 3rd stage disc & blades = (187.18+5.415) = 192.595 N

$\therefore$ Mass of 4th stage disc & blades = (91.14+3.913) = 95.053 N

& Mass of shaft = 1.1 kg

For calculating reactions at bearings



Total radial load acting on roller bearing **Fr$_{roller}$ = 3518.2 N = 3.52 kN**

Total radial load acting on ball bearing **Fr$_{ball}$ = 3477 N = 3.47 kN**

3.5 FORCES DUE TO ACTION OF GASES

Forces produced from static pressure of a gas are determined by the production of pressure of gas on the corresponding areas. The action of static gas pressure causes appearance of stresses of tension or compression, bending and torsion and axial forces. This may be in that case when various static pressures act on a part from both sides when there is area difference.

$P_{axial} = Q_1 - Q_2 + Q_3$

Axial force Q1 is the resultant from forces appearing on each stage

$Q1 = \sum_{i=1}^{4} Qst$

$Q_{st} = (P_{2i}A_{2i} - P_{1i}A_{1i}) + m\Delta C$

Assuming axial velocity is constant in compressor

$\therefore$ mΔC=0

Pressure after downstream of compressor = 33.5±0.5 = 34 bar

$\therefore$ P_{02} = 34 bar

Taking compression ratio = 23

$\therefore$ $r = \frac{P02}{P01} = 23$

$\therefore$ $\boldsymbol{P_{01}}$ **= 1.478 bar**

Now, for ramming effect

Assuming it as isentropic process

$$\frac{P0a}{P01} = \left[\frac{T0a}{T01}\right]^{\gamma/(\gamma-1)}$$

T_{01} **= 324.246 K** (stagnation temperature before 1st stage of LPC)

Now, for calculating T_{02}

$$\frac{P01}{P02} = \left[\frac{T01}{T02}\right]^{\eta_c \gamma/(\gamma-1)}$$

Taking polytropic efficiency of compressor = 0.87 & assuming it as an isentropic process

∴ $T_{02} = 908.527\ K$ (stagnation temperature after (3th stage of LPC)

Assuming

polytropic efficiency of LPC = 0.89

$$\frac{5.173}{1.478} = \left[\frac{(T_{02})_{LPC}}{324.25}\right]^{0.89*1.44/(1.44-1)}$$

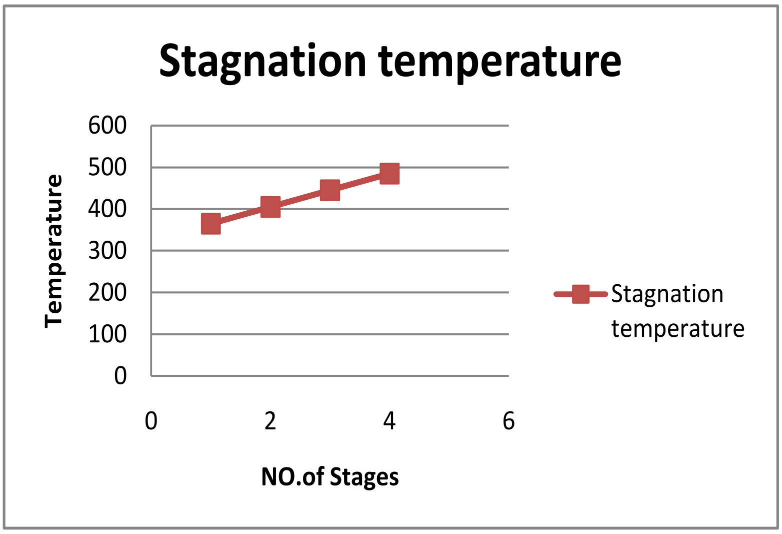
∴ $(T_{02})_{LPC}$ **= 484.775 K** (stagnation temperature after 4th stage of LPC)

∴ Stagnation temperature after 1st stage = 364.68 K

∴ Stagnation temperature after 2nd stage = 404.81 K

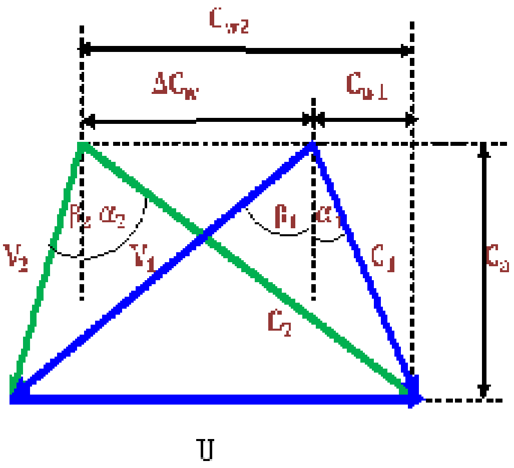
∴ Stagnation temperature after 3rd stage = 444.94 K

∴ Stagnation temperature after 4th stage = 484.78 K



Velocity triangle for LPC

<u>For 1st stage</u>



At max rating IGV's are fully opened

$\therefore \quad \alpha_1 = 0$

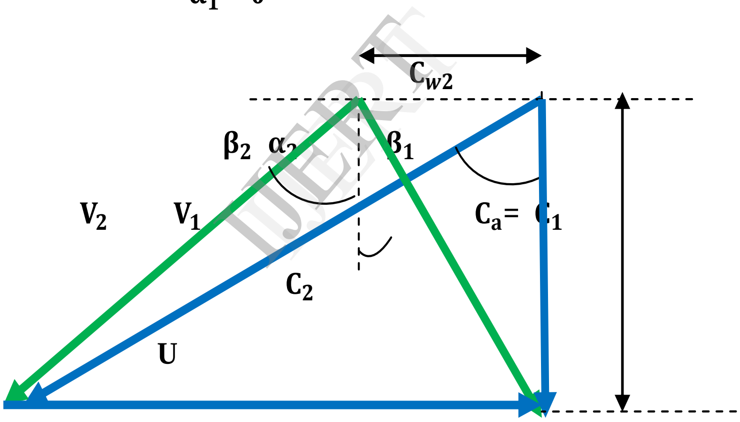


Fig:Velocity triangle for 1st stage LPC

$\lambda U(\Delta C_w) = C_p (T_0)_{stage}$ ....(λ= work done factor)

for 1st stage **λ= 0.98**

$$\Delta C_w = \frac{1004 \times 40.13}{0.98 \times 365.7} = \mathbf{112m/s}$$

$$\frac{P03}{P01} = \left[\frac{T03}{T01}\right]^{\eta_{stage}\ \gamma/(\gamma-1)}$$

Assuming polytropic efficiency of 1st stage = 0.9

$$\frac{P03}{1.478} = \left[\frac{364.68}{324.24}\right]^{0.9*1.4/(1.4-1)}$$

∴ $P_{03} = 2.062$ ***bar*** (Stagnation pressure after 1st stage)

$$\frac{P2}{P01} = \left[\frac{T2}{T01}\right]^{\gamma/(\gamma-1)}$$

∴ $P_2 = 1.764$ ***bar*** (Static pressure after 1st stage rotor)

$$\frac{P1}{P2} = \left[\frac{T1}{T2}\right]^{\gamma/(\gamma-1)}$$

∴ $\mathbf{P_1 = 1.213}$ **bar** (Static pressure before 1st stage rotor)

<u>For 2nd stage</u>

$(\Delta T_0) = 40.13$ K & $\lambda = 0.93$

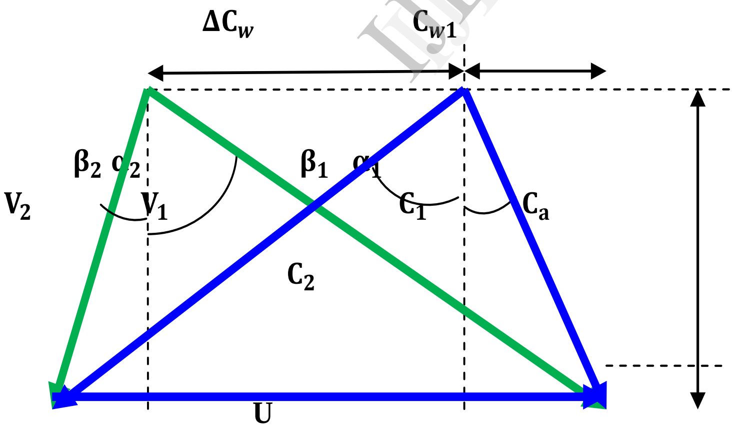
By using ,

$$(\Delta T_0) = \frac{\lambda}{C_p} U C_a (\tan\beta_1 - \tan\beta_2)$$

$\tan\beta_1 - \tan\beta_2 = 0.6345$ ……………………….(a)

using Degree of reaction (DOR) = $\frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2)$

$\beta_1 = 57.84$ & $\beta_2 = 43.71$



Using $\frac{U}{C_a} = \tan\alpha_2 + \tan\boldsymbol{\beta_2}$

$\boldsymbol{\alpha_2 = 45.08}$

& $\frac{U}{C_a} = \tan\alpha_1 + \tan\beta_1$

$\alpha_1 = 20.22$

$(T_1)_{2nd\ stage} = (T_{01})_{2nd\ stage} - \frac{C_1^2}{2C_p} = 344.96$ K (Static temperature before 2nd stage rotor)

$(T_2)_{2nd\ stage} = (T_{02})_{2nd\ stage} - \frac{C_2{}^2}{2C_p} = 370.06$ K (Static temperature after 2nd stage rotor)

$$\frac{P03}{2.062} = \left[\frac{404.81}{364.68}\right]^{0.9*1.4/(1.4-1)}$$

P_{03} = 2.865 bar …………………(Stagnation pressure after 2nd stage)

$\frac{P2}{P01} = \left[\frac{T2}{T01}\right]^{\gamma/(\gamma-1)}$ = 2.17 bar……………………(Static pressure after 2nd stage rotor)

$\frac{P1}{P2} = \left[\frac{T1}{T2}\right]^{\gamma/(\gamma-1)}$ =1.697 bar……………….. (Static pressure before 2nd stage rotor)

For 3rd stage

(ΔT_0) = 40.13 K & λ= 0.88

By using ,

$$(\Delta T_0) = \frac{\lambda}{C_p} U\, C_a\, (\tan\beta_1 - \tan\beta_2)$$

$\tan\beta_1 - \tan\beta_2 = 0.6705$ …………………………..(a)

$\beta_1 = 52.74$ & $\beta_2 = 32.8$

$$(T_1)_{3rd\ stage} = (T_{01})_{3rd\ stage} - \frac{C_1{}^2}{2C_p}$$

$$= 404.81 - \frac{221.98^2}{2*1004}$$

$(T_1)_{3rd\ stage}$ = 380.27 K (Static temperature beforer 3rd stage rotor)

$(T_2)_{3rd\ stage} = (T_{02})_{3ed\ stage} - \frac{C_2{}^2}{2C_p} = 397.65$ K (Static temperature after 3rd stage rotor)

$\frac{P03}{P01} = \left[\frac{T03}{T01}\right]^{\eta_{stage}\ \gamma/(\gamma-1)}$ = 3.858 bar Stagnation pressure after 3rd stage)

$\frac{P2}{P01} = \left[\frac{T2}{T01}\right]^{\gamma/(\gamma-1)}$ = 2.692 bar (Static pressure after 3rd stage rotor)

$$\frac{P1}{2.692} = \left[\frac{380.27}{397.65}\right]^{1.4/(1.4-1)}$$

P_1 = 2.302 bar (Static pressure before 3rd stage rotor)

For 4th stage

(ΔT_0) = 40.13 K & λ= 0.83

$(T_1)_{4th\ stage}$ = 420.82 K (Static temperature before 4th stage rotor)

$(T_2)_{4th\ stage}$ = 436.516 K (Static temperature after 4th stage rotor)

P_{03}= 5.056 bar (Stagnation pressure after 4th stage)

P_2= 3.609 bar (Static pressure after 4th stage rotor)

P_1= 3.175 bar (Static pressure before 4th stage rotor)

Axial force on compressor is as follows $P_{axial} = Q_1 - Q_2 + Q_3$

$Q_{st} = (P_{2i}A_{2i} - P_{1i}A_{1i}) + m\Delta C$

$Q_{st1} = (P_{21}A_{21} - P_{11}A_{11}) + m\Delta C = 19.702$ kN

$Q_{st2} = (P_{22}A_{22} - P_{12}A_{12}) + m\Delta C = 12.573$ kN

$Q_{st3} = (P_{23}A_{23} - P_{13}A_{13}) + m\Delta C == 13.644$ kN

$Q_{st4} = (P_{24}A_{24} - P_{14}A_{14}) + m\Delta C = 16.471$ kN

$Q_1 = Q_{st1} + Q_{st2} + Q_{st3} + Q_{st4} = 19.702 + 12.573 + 13.644 + 16.471 = 62.39$ kN

3.6 FORCES ACTING ON TURBINE ROTOR

$P_{axial} = Q_1 + Q_2 - Q_3 - Q_4$

$Q_1 = P \times A$

$\therefore Q_2 = \Delta P \times A$

$\therefore Q_3 = m\,(C_2 - C_1)$

$\therefore Q_4 = P \times A$

Force Q_1 acts on the left on annular surface of the disk

Assuming it as pressure vessel with thickness 0.8 mm

Using equation

$$t = \frac{P \times d}{2 \times \sigma_t \times \eta}$$

$$P = \frac{2 \times 0.8 \times 10^{-3} \times 269.5 \times 10^{6} \times 0.89}{524 \times 10^{-3}}$$

$$P = 7.2 \times 10^{5} \text{ Pa}$$

Assuming 20% pressure losses & finding out required areas

$\therefore$ Q1 = 40.44 kN

For calculating forces caused by difference in pressure of gas before and after the blades of turbine wheel.

4 BEARING SELECTION

$Fr_{ball} = 3.47$ kN

$Fa_{ball} = 3.21$ kN

Now C= dynamic load carrying capacity

$$C = P \times (L_{10})^{1/3} \times \text{Load factor}$$

$$C = 7.1 \times (2030.58)^{1/3} \times 1.4$$

$\therefore$ C= 98210 N = 98.21 k N

For Front support Roller Bearing :

Average life of roller bearing = 3000 hrs

$$L_{10} = \frac{60 \times 11000 \times 3000}{10^{6}}$$

$\therefore$ L_{10} = 2030.58 million rev

Now C= dynamic load carrying capacity

$$C = P \times (L_{10})^{3/10} \times \text{Load factor}$$

$\therefore$ C= 48512 N = 48.512 k N

5 CONCLUSION

In analytical design, by increasing numbers of ball, decreasing ball diameter, and changing the contact angle, the life in working hours can be increased. From the results of analytical design and analysis it can be seen that life of bearing is nearly same in both cases. It can be further increased by changing the parameters, material and lubrication of the Bearing. In this paper the proposed work focused to calculate the axial and radial forces acting on front & rear bearing of LPCR and also calculated the bearings parameters, which are useful for bearing selection.

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