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FATIGUE ANALYSIS AND DESIGN OF DIFFERENT COMPRESSOR ROTOR BLADE OF AN ORPHEUS ENGINE

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Abstract: *This paper "Fatigue Analysis and Design of Different Compressor Rotor Blade of an Orpheus Engine" is carried out in blade shop department, Engine Division, Compressor rotor blades are made up of aluminium and titanium based super alloys, is mounted on the rotor disc of compressor assembly unit. The purpose of compressor rotor is to raise the pressure of incoming air to have an efficient combustion in the combustion chamber to generate enough power to propel the aircraft. Moreover the Orpheus engine speed between 5000 to 7000 rpm is the critical rpm which is due to the 2nd and 3rd stage of rotors. It is therefore becomes mandatory to carry out fatigue testing on every production batch of indigenously developed forging of rotor-2 and rotor-3 blade before fitment on to the engine. Presently the rate of rejection during fatigue testing is up to 70%. The proposed paper is an attempt to reduce the rejection rate of compressor rotor blades stage-2 and 3 comparing the results through structural analysis procedures may help us to provide suggestions for increasing the fatigue life of the rotor blades. As a result this paper comes up with recommendations to improve the fatigue life of blades by improving the surface finish of blade by introduction of manual buffing operation on blade aerofoil after glass bead preening. On implementation the rejection rate is expected to be reduced to less than 5%. As a consequence we see timely completion of yearly production schedule, high productivity and employee morale.*

Keywords: *Fatigue analysis, Rotor blades, ORPHASE engine, PARETO Analysis***,** *CATIYA, AUTOCAD*

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1. INTRODUCTION

The components considered under this paper work titled **“**Fatigue Analysis and Design of Different Compressor Rotor Blade of an Orpheus Engine**”** are aero engine compressor rotor blades from aluminium alloy (MSRR8007) and titanium alloy forgings indigenously developed by F&F Division (HAL). Compressor rotor blades stage-2 and stage-3 are used in the second and third stage of compressor assembly unit of Orpheus engine. The Orpheus engines are being manufactured at Engine Division since 1957 under license from Rolls-Royce, UK and are used to power the Kiran Mark II trainer aircraft.

Orpheus engine is a turbojet engine having seven stages of axial compressor, which are driven by a single stage turbine. The main rotating assembly comprises of single unit in which the compressor rotor is coupled by a rigid shaft turbine wheel with maximum rotational speed of 10,000rpm and the entire rotor system is mounted on two bearings.

It consists of the following main components.

1. Air intake
2. Accessory drive
3. Seven stage axial compressor
4. Can annular combustion chamber
5. Single stage turbine
6. Exhaust system

The compressor unit includes

1. Rotor-In the rotor blades the velocity of the flow of air increases because of the motion imparted to the air, and the pressure increases because of the configuration of the blades (Divergent exit).
2. Stator (stationary vanes)-in the stator vanes the velocity is transforms into pressure because of the divergent air path and the flow is straightened.

<u>Orpheus Engine Main Characteristics</u>

Maximum Diameter (m)	:	0.925 m
Length (m)	:	2.290 m
Weight (kg)	:	420 Kg
Power (shp)	:	4200 lbs
Specific Fuel Consumption (kg/shp/hr)	:	1.106 lb/hr
Engine RPM	:	9500 RPM

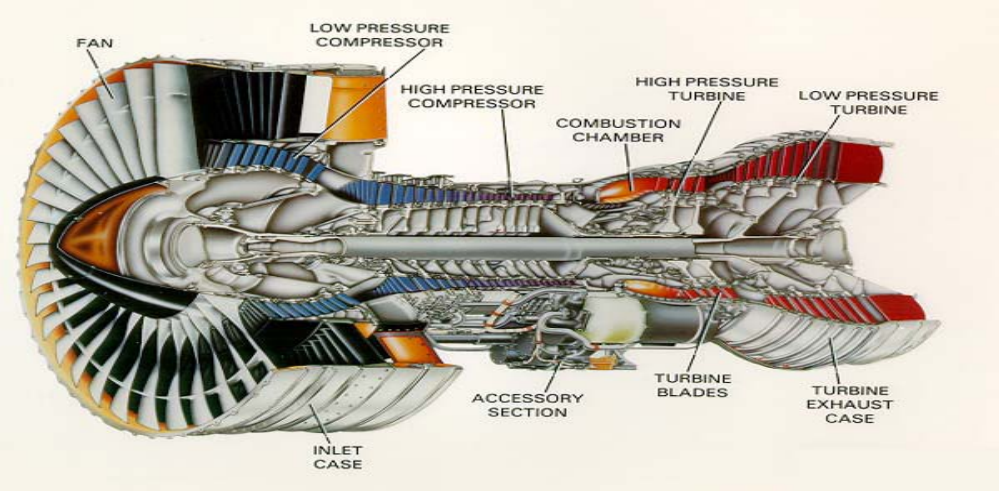

Figure 1: Engine Parts & Sectional View

2. PROBLEM ON HAND

Compressor rotor blades stage-2&3 are mounted on the rotor disc of compressor unit. The rotor blades provide the energy of compression. Hence, a compressor has to work against the pressure gradient, where as a turbine has to work along the pressure gradient that is why the compressor module, particularly the disc and rotor blades are severely loaded mechanically. The failure of any one of the compressor rotor blade would result in catastrophic engine failure affecting the safety. More the Orpheus engine speed between 5000 & 70000rpm is the critical rpm which is due to the 2nd and 3rd stage of compressor rotors .It is therefore becomes mandatory to carry out fatigue test o every production batch of rotor-2 and rotor-3 before fitment on to the engine. These blades are subjected to fatigue testing (Destructive type) in fatigue test to certify the values of these blades an aero engine to recommending for rejection of whole batch based on the fatigue report of simple six blades selected randomly from a manufactured batch, which is causing the severe shortage of these blades for repair and overhaul requirement for the year 2012/2013.

Defects in the Component

Values obtained after fatigue test of compressor rotor blade stage-2

Desired mean log life=9.49(min)

Obtained mean log life <9.49(min)

Desired “af” value =2.721 (min)

Obtained safe “af” value<2.721 (min)

Desired standard deviation =0.342 (max)

Obtained STD deviation >0.342 (max)

Values obtained after fatigue test of compressor rotor blade stage-3

Desired mean log life=9.57 (min)

Obtained mean log life<9.57 (min)

Desired “af” value=2.575 (min)

Obtained safe “af” value <2.575

Desired standard deviation =0.485 (max)

Obtained STD deviation >0.485 (max)

Cracks are developed at lower level of amplitude of vibration which leads to low fatigue life values as described above

The Orpheus engines are being manufactured at engine Division since 1957 under license from Rolls Royce, UK and are used to power the Kiran Mark II trainer aircraft.

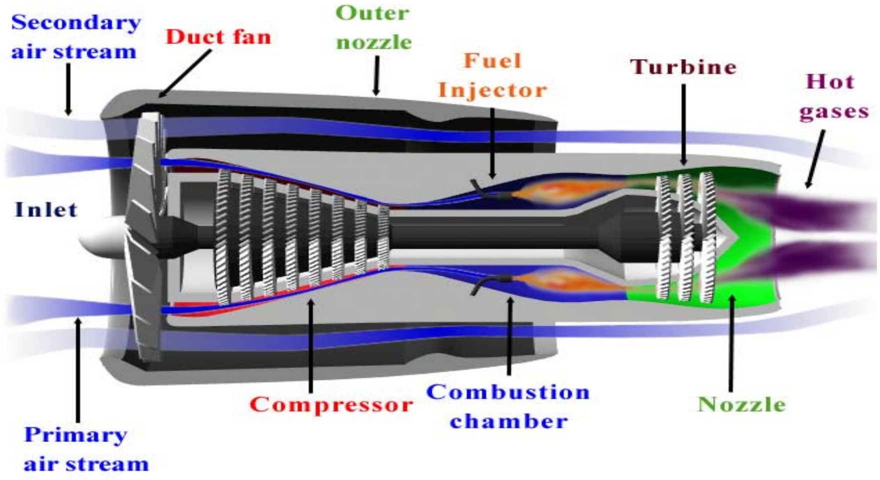

Figure 2: Turbojet Engine

3. CRITICALLY OF THE PROBLEM

The frequent and repeated rejection (up to 70%) of compressor rotor blades stage-2&3 of Orpheus engine due to premature failure of blades in vibratory fatigue testing (operation 310) is to be considered seriously. Table 1 shows the rejection in fatigue test for the last 3 years.

Table 1: Rejections in Fatigue Test for The Last 3 Years

Year Considered	No of sets manufactured	No of batches rejected
2009/2010	10+10	8+9
2010/2011	15+15	12+12
2011/2012	12+15	10+10
Average percentage of rejection	72.59%	

The cost structure of part is as follows:

Total final component cost of the part

Compressor rotor blade stage-2: Rs 18984/ part

Compressor rotor blade stage-3: Rs 16748/ part

The above results in wastage of man hour, machine hour and total productivity of the system, as the blades were getting rejected at final operation after the complete processing of blade.

It may be seen from rejection analysis that the production yield of these blades continuous to be too low warranting personal intervention to study the possibilities of improving the fatigue life of blades, to avoid fatigue test failures.

4. PRINCIPLE OF THE ORPHEUS ENGINE

It is basically a straight flow single spool of 17KN thrust class with multi stage axial flow compressor driven by single stage turbine. A turbojet engine is used primarily to propel aircraft. Air is drawn into the rotating compressor stage to a higher pressure before entering the combustion chamber. Fuel is mixed with the compressed air and ignited by a flame in the eddy of a flame holder. This combustion process significantly raises the temperature of the gas. Hot combustion products leaving the combustor expand through the turbine where power is extracted to drive the compressor. Although this expansion process reduces the turbine exit gas temperature and pressure, both parameters are usually still well above ambient conditions. The gas stream exiting the turbine expands to ambient pressure via the propelling nozzle, producing a high velocity jet in the exhaust plume. If the momentum of the exhaust stream exceeds the momentum of the intake stream, the impulse is positive, thus, there is a net forward thrust upon the airframe.

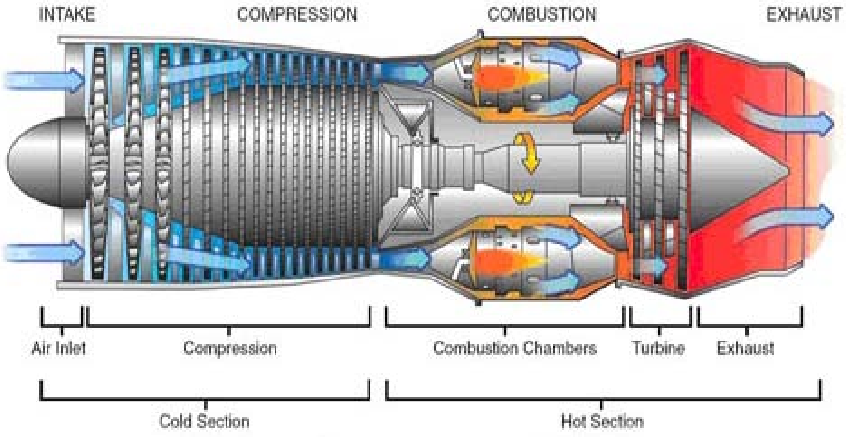

Figure 3: Typical Pictorial Representation of Single Spool Turbojet Engine

5. COMPRESSOR

The purpose of the compressor is to obtain good combustion efficiency by a supply of air under pressure. The compressor ensures this supply of air under pressure. In compressor unit there are two types of blades one is rotary and other is stationary. The purpose of rotary is to increase the kinematic energy of the incoming air and the purpose of stationary blades is to guide the incoming and outgoing air along with increase in pressure due to its aerodynamic shape and divergent exit. The project under consideration is of rotary (Orpheus compressor blades stage-2 & stage-3).

The marked change in blade size from front to rear in a high pressure ratio compressor depends on lot of factors. It is desirable to keep the axial velocity approximately constant throughout the compressor. With the density increasing as the flow progresses through the machine, it is therefore necessary to reduce the flow progress through the machine and hence the height of blade.

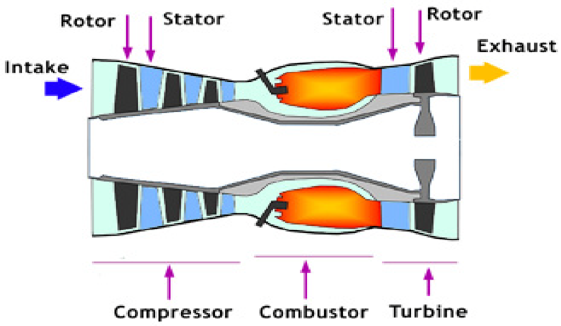

Figure 4: Row of Stator & Rotor Blades

Details of Operation:

- Remove all burs and sharp corners edges.
- Polish ballads form
- Lightly breakdown sharp edges only.
- Blend and polish fillet and edges radii at base of aerofoil section. Polish fillet radii at trailing edge to MT 37B (Manufacturing Technique)
- Polish platform face.
- Radius root serrations to MT 39 (Manufacturing Technique)
- After polishing max surface roughness of remaining surfaces 50 microns inches.

Operation 210 & 220: Rough and finish grind blade length.

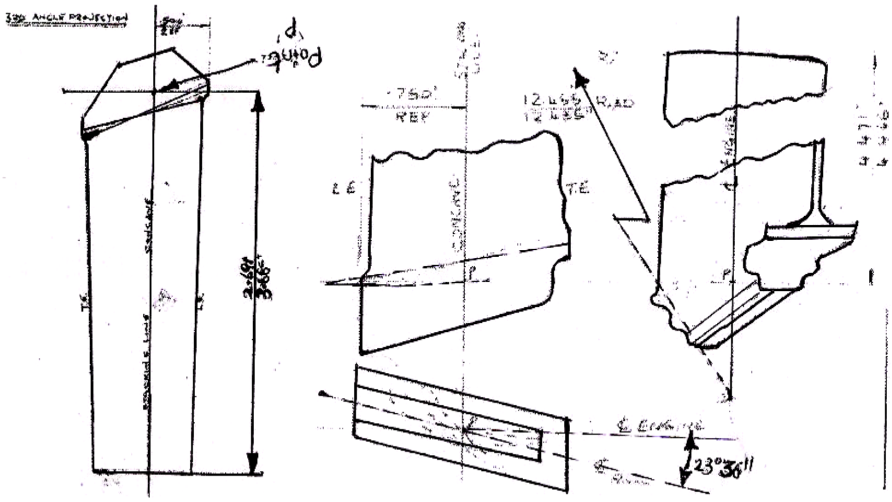

Figure 5: Rough and Finish Grind Blade Length

- Operation 240: Ref data card no L/015 GBP Time and pressure control Glass Bead Peening blade profile and top surface of flat form.

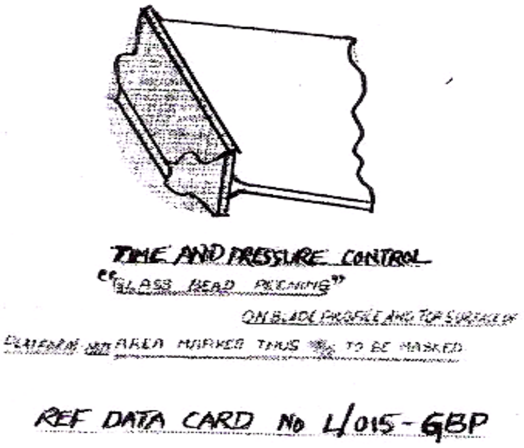

Figure 6: Control Glass Bead Peening

Details of procedure for fatigue testing explained below

- The blade is clamped at the root with a pre determined torque.
- A mark is made in the tip of the blade.
- Align the microscope in line with the tip of chord of the blade at leading edge.
- The eyepiece is focused such that a clear image of the mark is obtained. The travelling microscope is moved until one end of the mark eyepiece. The scale reading of the microscope is noted down as zero ref point.
- Switch on the amplifier at a very low power rating.
- By adjusting the length of the exciter rod and the connecting upright rod the system can be tuned to the particular natural frequency of the blade.
- But the initial value "af" is taken should be less than one half that of the failing "af"
- The process is repeated until failure occurs.
- The blade frequency is continuously monitored and when it is found to have dropped by 2% from original setting up frequency, the test is brought to rest and failure is assumed to have taken place.

From the above procedure the following data is observed.

Miners hypothesis is used for comparing the fatigue strength of the sample batch with the standard reference batch,

1. Test frequency f (c.p.s)
2. Tip amplitude a (mm)
3. The magnitude of the amplitude steps (r)
4. The time spent at each step (Ns)
5. The time spent at failing amplitude (nr)

Mean log life, standard deviation of the sample batch and safe "af" values of the given batch estimated. These values are compared with standard reference batch for the acceptance of the given batch.

6. FATIGUE ANALYSIS

Fatigue: Fatigue is defined as the progressive deterioration of the strength of a material or structural component during service such that failure can occur at much lower stress levels than the ultimate stress level. Fatigue is a dynamic phenomenon which initiates small (micro) cracks in the material or component and causes them to grow in to large (macro) cracks; these, if not detected, can result in catastrophic failure.

Fatigue Life: ASTM defines fatigue life, N_f as the no. of stress of a specified character that a specimen sustains failure of a specified nature occurs. One method to predict fatigue life of materials is the uniform material law (UML). For some materials there is a theoretical value for stress amplitude below which it will not fail under any no. of cycles, called a fatigue limit, endurance limit or fatigue strength.

Probabilistic nature of fatigue: As coupons sampled from a homogenous frame will manifest variation in their no. of cycles to failure, the S-N curve should more properly be an S-N-P curve capturing the probability of failure after a given no. of cycles of a certain stress. Probability distributions that are common in data analysis and design against fatigue include the lognormal distribution, extreme value distribution, Birnbaum- Saunders distribution and Weibull distribution

Fatigue life analysis:

Steps Involved in Fatigue Life Calculation:

1. We have our Max principal (S_{max}) and Min Principal Stress (S_{min})
2. Calculate S_r (Stress range) ; $S_r = S_{max} - S_{min}$
3. And the S_a (Stress Amplitude) ; $S_a = \frac{Sr}{2}$
4. Ultimate tensile strength (UTS) of Titanium alloy we had 916 N/mm
5. Fatigue limit, S_f = 1.6*Ultimate tensile strength
6. b is the slope of s – n curve
7. $Nf^b = \frac{Sa}{2^b * Sf}$
8. From that find "N_f" the Fatigue life time period in hours

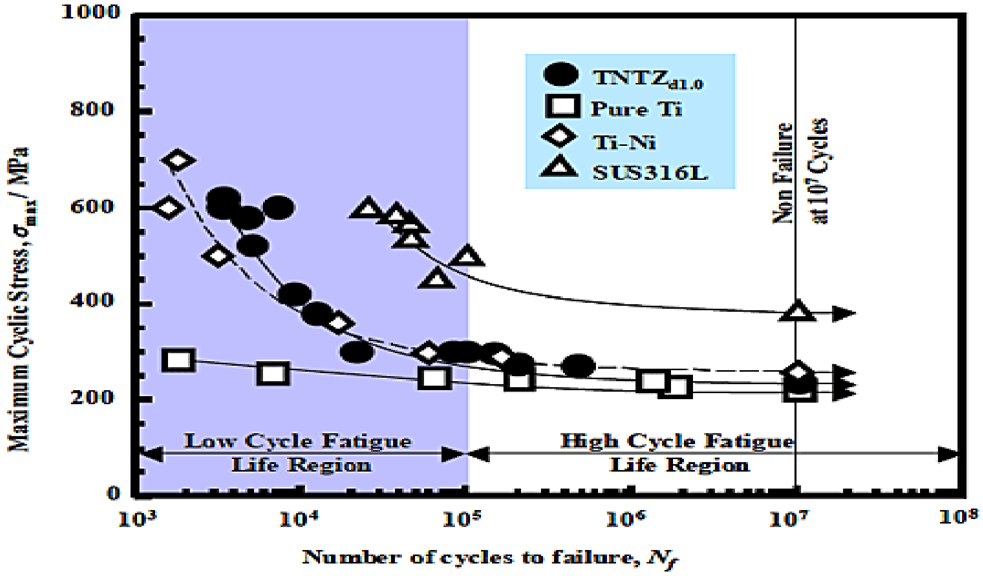

Figure 7: S-N Curve

S_{max} = 107 MPa; % Max Principal Stress

S_{min} = 25.8 MPa; % Min Principal Stress

$S_r = S_{max} - S_{min}$; %Stress Range

$S_a = S_r/2$; %Stress Amplitude

UTS = 916; % Ultimate strength

% 1.6 times the UTS is S_f

S_f = 1.6 * UTS;

The Value of b depends on the Material

b = -0.301; % slope of s-n curve

Stress Range, $S_r = S_{max} - S_{min}$

= 107 MPa – 25.8 MPa = 81.2 MPa

Stress Amplitude, $S_a = S_r/2$

= 81.2 / 2 = 40.6 MPa

Fatigue limit, S_f = 1.6 * 916 MPa (UTS)

=1456.6 MPa.

b = -0.301; % slope of s-n curve (from figure 7.12)

% the value of 2^b is calculated for calculation pw = 2^b;

% b th root of N_f (Fatigue life in Hours)

% has to be calculated

N_f = Sa/(pw * S_f);

N_f = nth root (N_f,b)

N_f = 7.4706e+004 =74,706 flight hours

7. PARETO ANALYSIS

Alfredo Pareto (1848-1923) conducted extensive studies of the distribution of wealth in Europe. He found that there were a few people with lot of money and many people with little money. This unequal distribution of wealth became an integral part of economic theory. Dr. Joseph juran recognized this concept as a universal that could be applied to many fields. He coined the phrase vital few and useful many. A Pareto diagram is a graph that ranks data classifications in descending order from left to right. Pareto diagram are to be distinguished from histograms by the fact that the horizontal scale of a Pareto diagram is categorical, where as the scale for histogram is numerical. Pareto diagram are used to identify the most important problems. Usually 75% of the total results from 25% of the items.

Pareto analysis on compressor rotor blades rejection factors:

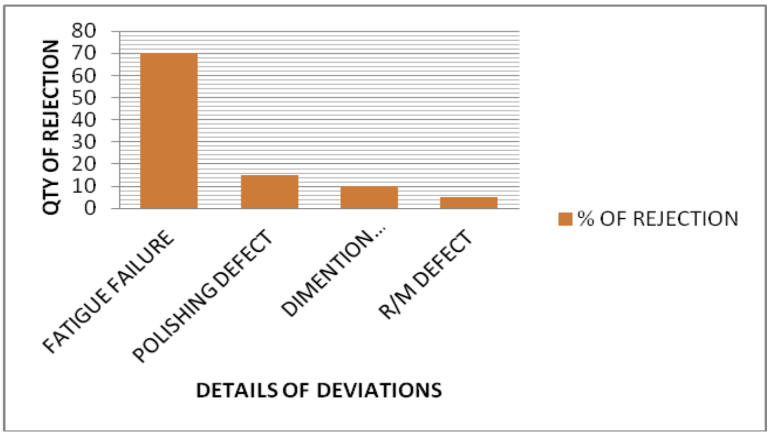

Figure 8: Pareto Analysis Chart

Cause and Effect Diagram

A cause-and-effect (C&E) diagram is a picture composed of lines and symbols designed to represent a meaningful relationship between an effect and its causes. It was developed by Dr. Kaoru ishikawa in 1943 and is sometimes referred to as an ishikawa diagram or a fishbone diagram because of its shape. Each major cause is further subdivided into numerous minor causes. For example, under work methods, we might have training, knowledge, ability, physical characteristics, and so forth. C&E diagrams are the means of picturing all these major and minor causes. C&E diagram for the compressor rotor blades stage 2&3 using four major causes

Result From Pareto Analysis

It is observed from Pareto analysis that the rejection of Compressor rotor blades stage 2&3 are due to

- Fatigue failure
- Dimensional deviations
- Raw material defects
- Polishing defects

8. RESULT FROM BRAIN STORMING

Brain storming session reveals different reasons responsible for the occurrence of the problem. So one by one causes are categorized and are framed on the cause and effect (Fish bone) diagram to find out the root cause of the problem.

Design data for drafting:

Table 2: Design Data for Drafting

Parameters	Dimension
Outer radius of rotor disc (centre)	0.314 m
Inner radius of rotor disc (centre)	0.062 m
Max. diameter of the rotor compressor disc	0.918 m
Top width of the blade	0.075 m
Tool used	CATIA V5 R20
Total compressor with blades weight	52 Kg
Individual blade weight	0.3 kg

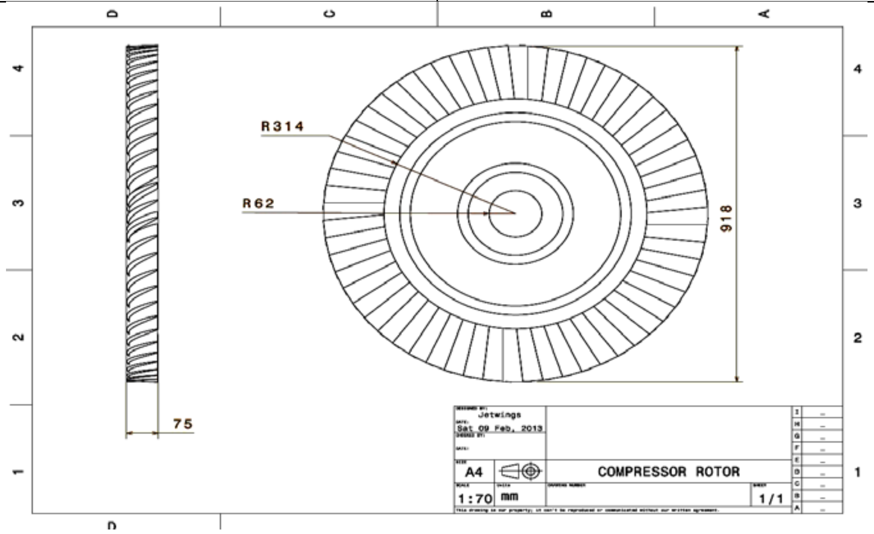

Figure 9: Rotor Blade

Table 3: Chemical Composition

Component	**Weight (%)**
Titanium	balance
Carbon	0.10
Iron	0.40
Vanadium	3.50 – 4.50
Nitrogen	0.05
Hydrogen	0.015
Oxygen	0.020
Others	0.40

Mechanical Properties

Table 4: Properties of titanium alloy 6Al-4V

Ultimate Tensile strength	950 MPa
Tensile yield strength	880 MPa
Modulus of Elasticity	113.8 GPa
Poisson’s Ratio	0.342
Shear Modulus	44 GPa
Shear strength	550 MPa
Density	4.43 g/cc
Elongation	14 %
Hardness(HB) Rockwell	36 (metric)
Reduction area	36%
Heat treatment condition	Annealing
Melting temperature	1604 c – 1660 c
Electrical resistivity	0.000178 ohm-cm
Fatigue strength	240 MPa

Table 5: Analysis Data of Compressor Disc

PARAMETER	**TOOL / VALUE**
Tool used	MSC Nastran / Patran
Shaft speed	6500 RPM
Centrifugal force	51 KN
Material	Titanium alloy (grade 5)
Analysis done	Linear static condition
Angular velocity	(2Nπ) / 60 = 680.333 rad/sec

9. GAINS OF THE STUDY

Reduction in the rejection rate

Table 6: Rejection rate comparison before and after implementation

Before implementation	70%
on successful implementation	5%

Reduction in baking temperature

Table 7: Baking Temperature after Implementation

Before implementation	195^{o}C
After implementation	107^{o}C

Improvement in the quality and fatigue properties of rotor-2 and rotor-3 blades:

Table 8: Surface Finish Comparison Before and After Implementation

Before implementation	1.75 micron
After implementation	0.2 micron

Average fatigue life data like mean log life and safe “af” value for rotor-2 blades

Table 9: Average Fatigue Life Data Like Mean Log Life and Safe “af” Value for Rotor-2 Blades

Description	Mean log life (9.49min)	Safe “af” value(2.721min)
Before implementation	Less than 9.49	Less than 2.721
After implementation	More than 9.49	More than 2.721

Average fatigue life data like mean log life and safe “af” value for rotor-3 blades

Table 10: Average Fatigue Life Data Like Mean Log Life and Safe “af” Value for Rotor-3 Blades

Description	Mean log life (9.57min)	Safe “af” value(2.757 min)
Before implementation	Less than 9.57	Less than 2.757
After implementation	More than 9.57	More than 2.757

Cost saving

Table 11: Cost Saving

Part name	Material cost/part cost	Final component cost
Rotor stg-2	9624	18984
Rotor stg-3	7617	16748

Table 12: Cost Savings per Annum

Component name	No. of blades saved from rejection	Total cost
Rotor stg-2	184	34,93,056.00
Rotor stg-3	328	54,93,344.00
Total saving/annum		89,86,400.00

10. CONCLUSIONS

ORPHEUS Engine 70105 is a basically straight flow turbojet engine, used to power the KIRAN MARK II trainer aircraft under the license from Rolls-Royce, UK. The Orpheus engine is single spool axial flow turbojet engine which develops a thrust of 1875 kg. The engine contains seven stage axial flow compressor to compress the atmospheric air to obtain the required pressure ratio for efficient combustion.

Our study of this Paper is restricted to stage-2 and stage-3 compressor rotor blades respectively. Our project involves the study, analysis of the factors pertaining to the fatigue strength of rotor blade and change in processes to improve the fatigue life of rotor blades are concluded. The various causes for the decrease of fatigue life are identified and the solutions for those problems are established during the course of study.

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