Aero-Engine Compressor Rotor Development through Reengineering based Product Development Cycle

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Abstract

Present paper details an aero-engine centrifugal compressor rotor development through reengineering based product development cycle to overcome obsolescence and to augment in-house technology development program and to improve the product performance such as fatigue life, efficiency, cost etc. by usage of superior material/technology while keeping the overall envelope, mass and center of gravity similar to the existing one. The four phase product development cycle started with assessment of requirement of the product and benchmarking where products of similar nature are identified, studied and ideas so developed are utilized for designing the part. The product development cycle continued through product design which involved design calculations, modeling, drawing generation and structural integrity evaluation through FE analysis. In the prototype testing phase of the product development cycle, compressor rotor has been fabricated through forging route and its structural integrity has been validated through cyclic spin test at its operating speed as well as 15\% and 22\% over-speeds in the rig. Satisfactory performance during these tests without any distress has demonstrated the adequacy of design. The compressor rotor has been fitted in starter engine and was then subjected to qualification tests successfully before it was cleared for production. Production of the compressor rotor is the culminating phase of the product development cycle.

Keywords: Reengineering, Product Development Cycle, Centrifugal Compressor

1. Introduction

The product development cycle includes all the activities leading to the realisation of the particular product and introduction of the same to the market with the goal to provide the customer with the best possible product at the lowest possible price and as soon as possible. Ronald D Cadwell et al. (1995) introduced reengineering in order to improve the product development cycle. Hammer M et al. (1993) gave a definition for Reengineering and is: “The fundamental rethinking and radical redesign of business process to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service and speed”. Reengineering examines entire product development cycle in search of bottleneck tasks and redundant operations. This led to four phase product development cycle that consists of assessment and benchmarking, product design, prototype testing and production. Product features have to be prioritised according to their business value and the technical feasibility as per reengineering perspective.

A Jet Fuel Starting system is designed for starting main engine without the need for external ground support services. During main engine start-up the starter drives the engine up to light up speed and then continues to assist during the acceleration phase. The aircraft engine becomes self sustained in approximately 30 secs. One of the main parts of the starter is a centrifugal compressor rotor wheel made of steel inducer and aluminium impeller positioned with respect to each other by dowel pins and spring washer which has to be replaced after every 3300 starts. This aero-engine centrifugal compressor has potential of huge cost saving through simplistic manufacturing method and life improvement and the development can augment in-house technology development program. Present paper details the development program of this compressor through reengineering based product development cycle. Product development cycle started with need assessment where the requirements of the customers are identified through data collection and benchmarking.

Product design phase of the development cycle is the most involved part. This requires elaborate knowledge on the loads and operating conditions and needs to address all the challenges of development. During every start-up and shutdown of a starter used for starting the main engine, the compressor is subjected to centrifugal, thermal and gas bending loads which are categorized as steady loads and the dynamic
load, arising from pressure fluctuation leading to unsteady blade loading. The fatigue life under such conditions is to be computed accurately for maximization of the use of the component without compromising safety.

S. S. Manson and G. R. Halford (2006) distinguished Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) based on the relative amounts of plastic and elastic strains present. The LCF occurs as a result of JFS start/stop cycles and is predominant for rotors that operate under cyclic stresses. HCF failure occurs due to resonance condition caused by a periodic force which acts at a frequency corresponding to the natural frequency of component.

Compressors operate at very high speed making their design and validation process very complicated. Though they are designed based on open literature, meeting the stringent requirements of tip clearance, structural integrity and high life cycle make the design of every compressor highly challenging. It requires the developing team to carry out a thorough analysis and experimental validation to certify the component for airworthiness as safety aspect is of paramount importance in aircraft industry.

In the prototype testing phase of the product development cycle, compressor has to be fabricated and its structural integrity has to be validated through cyclic spin test at 105% of its operating speed as well as 15% and 22% overspeeds. Finally the compressor has to be fitted in engine for performance testing before cleared for aircraft application.

The compressor satisfactorily performance with respect to structural integrity and functional requirements and successful completion of prototype testing will pave way for airworthiness certification of the compressor and subsequent series production of the unit which is the culminating phase of the product development cycle.

2. Configuration

The starting system is basically a turbo shaft engine comprising two distinct sections - a gas generator and a starter (turbine/gearbox). The gas generator comprises the starter motor, the air intake assembly, the core engine including the compressor, combustor and HP turbine and is mounted on two oblique concave pre loaded ball bearings. The subject compressor rotor wheel is one of the major sub-assembly of the starter unit.

3. Methodology

Four phase product development cycle is adopted for the development of the compressor rotor. Reengineering is introduced after the first phase for assessment of the entire product development cycle.

3.1 Assessment and Benchmarking

Understanding the requirements of the customers through data collection forms the basis for assessment. The subject compressor rotor has been identified for reengineering due to long lead time in supply, erratic and short supply from OEM and high cost as well as a good number of replacement requirement. Through need assessment once the potential of a product is identified, benchmarking involves evaluation of similar available products in the market. Rather than starting from scratch, benchmarking helps the designer to start the design by studying the complete disassembly of existing product, if available, to determine the material, function, manufacturing process and cost of part. Since the product was available, it is decided to introduce reengineering to decide the product development cycle for the compressor development.

3.2 Reengineering

The reengineering process examined entire product development cycle and found that the steel inducer blades function as phonic wheel also for speed measurement of the rotor. This study eliminated the possibility of fabrication of compressor rotor in a single piece configuration with aluminum alloy and any change in number of rotor blades as this would lead to induction of a separate phonic wheel and major changes in controller programme.

In the present case as the need assessment and benchmarking phase identified and studied the potential of an existing compressor part, it is decided to start the design by studying the complete disassembly of existing product to determine the material, function, manufacturing process and cost of part. Further overall envelope, mass and centre of gravity have been maintained same as to the existing one though there were change in material and manufacturing methods to avoid chain of changes/modifications in the other subassemblies to minimize the cost of whole product development cycle.

Reengineering further examined entire product development cycle in search of bottleneck tasks and redundant operation. The biggest challenge was the non-availability of materials and tolerance bands, requiring the designer to carry out elaborate analyses to garner the data. The existing assembly of the impeller and inducer requires a spring washer to have a certain cone and numerical iterations are carried out to determine the cone angle required for proper functioning of the assembly. Spring washer has to be heated and assembled in heated condition for proper assembly. Assembly procedure has to be established
through an iterative experimentation approach and steps are taken to develop the facility for the same as it is identified as a bottleneck task. These activities have started well in advance so as to reduce the cycle time.

Once reengineering phase established the technical feasibility and best possible design methodology, product design phase is initiated.

### 3.3 Product Design

This phase encompass the activities such as selection of material, model and drawing generation and detailed numerical analyses. Proper material selection and manufacturing method have been decided at this stage to enhance the fatigue life of the component by four fold in comparison to the existing one.

#### 3.3.1 Material Checking

Existing compressor material is checked and found out that the inducer part confirms to steel and impeller part confirms to Al-Cu alloy.

#### 3.3.2 Detail Design

White light scanning is used to develop the model of the component. The tolerances are specified based on the aero-thermo analysis and experience of the designer.

#### 3.3.3 Drawing and Model Preparation

The 3D model and drawings of the compressor, inducer and impeller respectively have been generated using CATIA and AutoCAD software.

#### 3.3.4 Numerical Performance Analysis

Computational Fluid Dynamics analysis of the compressor rotor has been carried out for minimum, mean and max. metal condition to validate the profile configuration/tolerances and performance.

#### 3.3.5 Numerical Structural Integrity Analysis

1/15th cyclic symmetric sector of the wheel has been used for analysis to reduce the solution time. F W Wills (1986) and Thomas D L (1979) has shown in their respective papers that cyclic sector represent the whole wheel with the use of special boundary condition wherein cut boundary nodes of one sector are made to have same degree of freedom constrain with the other cut boundary of the cyclic symmetric sector.

#### 3.3.5.1 FE Model of Compressor

3D model of compressor was created in UG NX and imported to ANSYS FE package. 1/15th cyclic symmetry of the wheel is extracted from the 3D CAD model as shown in Figure-1.

By using this sector for analysis, number of degrees-of freedom in the resulting equations decreases by a factor equal to the number of blades in a bladed disk, without any compromise with modeling accuracy. Finite element model is developed as shown in figure-2 by meshing the sector with 10 node tetrahedral SOLID92 elements.

Grid density is kept constant and grid sensitivity analysis ensured the accuracy of the results.

#### 3.3.5.2 Structural Static Analysis

##### 3.3.5.2.1 Static Stress Analysis

Following loads are considered for the analysis:
- Centrifugal load due to rotation of compressor
- Pressure due to clamping load
- Thermal load due to temperature gradient
- Gas bending load
The material properties are applied by accounting the temperature variation in properties. Static stress analysis is carried out on the 1/15th cyclic sector model of the compressor at design as well as at different over-speed conditions. The von-Misses stress contours at 105% over-speed are shown in Figure-3 for five sectors.

![Von Mises stress at 105% of Design Speed](image)

The maximum stress along with factor of safety is presented in Table-1.

### Table 1: Stress Analysis Results for Static Load Conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Max. VM Stress (MPa)</th>
<th>Temp °C at max stress</th>
<th>FS_{2.0%}</th>
<th>FS_{UTS}</th>
</tr>
</thead>
<tbody>
<tr>
<td>105%</td>
<td>Impeller 309.83</td>
<td>54.39</td>
<td>1.06</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>Inducer 943.13</td>
<td>34.98</td>
<td>1.06</td>
<td>1.13</td>
</tr>
<tr>
<td>115%</td>
<td>Impeller 313.76</td>
<td>56.82</td>
<td>1.05</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Inducer 1001</td>
<td>35.18</td>
<td>0.99</td>
<td>1.06</td>
</tr>
<tr>
<td>122%</td>
<td>Impeller 326.19</td>
<td>56.82</td>
<td>1.01</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>Inducer 1034</td>
<td>36.88</td>
<td>0.96</td>
<td>1.03</td>
</tr>
</tbody>
</table>

The operating von Mises stresses at 105% design, 115% and 122% over-speed are within the elastic limit and adequate factor of safety is available. Further LCF life is estimated based on the stress results of 105% design speed load condition.

#### 3.3.5.2.2 LCF Life Evaluation

Fatigue life is estimated using Mason-Hirchberg universal slope equation as given below.

\[
\Delta \varepsilon = \left( \frac{3.5S_u}{E} \right) \left( N_f \right)^{0.12} + \left( D \right)^{0.6} \left( N_f \right)^{0.46}
\]

where,

- \( \Delta \varepsilon \): Total von Mises strain
- \( S_u \): Ultimate strength of the material
- \( E \): Young’s Modulus
- \( N_f \): Number of cycles to failure
- \( D \): Ductility coefficient

The mean stress effects are neglected as it is found that the life estimated is very high compared to the required life of 6500 cycles.

### Table 2: Fatigue life calculation

<table>
<thead>
<tr>
<th>Part</th>
<th>Total Strain</th>
<th>Calculated Fatigue Life (cycles)</th>
<th>Expected Life (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller</td>
<td>0.004706</td>
<td>220800</td>
<td>110400</td>
</tr>
<tr>
<td>Inducer</td>
<td>0.004667</td>
<td>220500</td>
<td>110250</td>
</tr>
</tbody>
</table>

Expected life is estimated as 50% of the calculated fatigue life to take care of the scatter in material properties, loading etc and is based on standard practice followed in-house.

#### 3.3.5.3 Dynamic Analysis

##### 3.3.5.3.1 Modal Analysis

A pre-stressed modal analysis is carried out, which takes into account the temperature effects, to find the natural frequencies (modes) and mode shapes during each mode of vibration. John M Vance (1988) showed in his book that critical speed occurs when natural frequency matches with a multiple of rotational speed of the component.

At engine operating conditions compressor would be subjected to external excitations. As per J. S. Rao (1998) the main sources of excitation are the integral order engine vibration and harmonic excitations caused by pressure fluctuations in the flow field. Modal analysis is carried out and Campbell diagram is plotted as shown in Figure-4.

![Campbell diagram](image)

Campbell diagrams are used to find the interference between natural frequencies and common exciting forces by plotting natural frequencies against rotor running speed.
3.3.5.3.2 Harmonic Analysis

For a resonance condition to occur in the bladed disc the two following conditions must be fulfilled.
- The excitation frequency must coincide with one of the disc natural frequencies.
- The mode shape of the actual natural mode must show the same relative amplitude phase shift between adjacent blades as excitation forces show.

As it is found from Campbell diagram that these conditions are not met, the HCF life is infinity.

3.4 Prototype testing and Concurrent Airworthiness Certification of Indigenously Developed Compressor Rotor

Airworthiness Certification is essential for any indigenously developed component before according clearance for fitment into airborne store. A series of rigorous qualification test has been carried out for material selection, forging, fatigue life, structural integrity and component performance validation. Major airworthiness qualification tests are given below:
- Design and configuration analysis verification
- Raw material level qualification
- Forging level qualification
- Finished component level qualification
- Starter unit level qualification

3.4.1 Test on Forging

The centrifugal compressor rotor wheel has a steel inducer part and an aluminium impeller part assembled together by using two dowels and a spring washer. Separate forgings are developed for impeller and inducer. Following tests are conducted on this forging before commencement of machining operation.
- Ultrasonic test
- Hardness
- Grain flow
- Tensile Test at room temperature
- Tensile Test at high temperature
- High cycle fatigue (HCF) at room temperature
- Stress rupture test at high temperature

Test results on the forging are meeting the stipulated requirements.

3.4.2 Cyclic Spin Test

Cyclic spin testing is carried out as per MIL E - 5007E to verify the estimated low cycle fatigue life. The compressor is tested at calculated equivalent speed after taking into account the temperature effect and pressure load on material strength. Calculated equivalent speed is 50000 rpm.

The cyclic spin test is done by spinning the compressor assembled with a cyclic spin mandrel, in the cyclic spin test rig at equivalent speed. Compressor and assembly of cyclic spin mandrel and compressor are dynamically balanced within 0.5 mm-g based on the calculations given in Balance quality requirements of rigid rotors-Part-1 (1940). Compressor and Cyclic Spin Mandrel are subjected to crack detection as per aerospace standards before and after the cyclic spin test. Wheel tip diameter is measured before the cyclic spin testing and after the completion of 6500 cycles to check for permanent growth, if any. Acceleration and deceleration rates of the compressor wheel are established based on the transient analysis results and the test rig limitation. Figure-5 shows the Test Cycle.

![Fig-5: Test Cyclic of Spin Test](image)

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>5000 rpm to 50000 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwell</td>
<td>5 seconds at 50000 rpm</td>
</tr>
<tr>
<td>Deceleration</td>
<td>50000 rpm to 5000 rpm</td>
</tr>
<tr>
<td>Dwell</td>
<td>5 seconds at 5000 rpm</td>
</tr>
<tr>
<td>No. of Cycles</td>
<td>6500 cycles</td>
</tr>
</tbody>
</table>

3.4.2.1 Cyclic Spin Test-NDT & Dimensional Inspection Results

- No dimensional growth observed after 6500 cycles.
- No distress observed on the component after 6500 cycles of spin test. Component is found free from crack checked through Fluorescent Penetrant Inspection method.
- This test satisfied the stipulated fatigue life requirements of compressor wheel.

3.4.3 Over-speed Test

Over-speed testing at 115% and 122% over-speed conditions is carried out as per MIL E-5007E to validate the structural integrity estimation. The test rig used is the same as that for cyclic spin testing. The equivalent speeds for overspeed test are:
- 115% equivalent speed : 57540 rpm
- 122% equivalent speed : 62060 rpm
Compressor is subjected to crack detection as per aerospace standard before the over-speed test. Bore and rim diameters are measured before and after overspeed test, at the same place, to check for permanent growth, if any. Compressor and assembly of compressor and overspeed mandrel are balanced within 0.5 mm-g. Compressor is subjected to crack detection after completion of each overspeed test. Compressor is spun in the rig for time duration of 5 minutes after attaining maximum speed for each overspeed case. Overspeed test is done for one cycle for each condition.

3.4.3.1 Overspeed Test-NDT & Dimensional Inspection Results

- No dimensional growth observed after 115% and 122% overspeed tests on the component.
- No distress observed on the component after 115% and 122% overspeed tests. Component is found free from crack checked through Fluorescent Penetrant Inspection method.
- The overspeed tests satisfied the stipulated structural integrity requirement of the air turbine wheel.

3.4.5 Performance Testing

To substantiate the performance consistency i.e. speed-torque characteristics of compressor, performance test was carried out after assembling the compressor into Starter Unit. The performance test is carried out in the testing facility and the starter unit performed consistently during qualification and acceptance test and the results are shown in figure-6. No dimensional growth observed after tests on the component. The compressor is found free from crack checked through Fluorescent Penetrant Inspection method.

![Fig-6: Compressor rotor performance in unit](image)

3.5 Production

Prototype testing determines whether any changes are required in the product before productionisation. Once it is confirmed that there is no changes, the prototype production makes way for final production. Figure-7 shows the final compressor supplied to the customer. Manufactured final compressor rotor has resulted in huge cost saving and life improvement through simplistic manufacturing method.

![Fig-7: Manufactured final compressor rotor](image)

4. Conclusions

The development of compressor rotor is a challenging task as serious design efforts are required for avoiding vibration problems and evaluating structural integrity. Reengineering based four stage product development cycle is successfully employed to develop an aero-engine compressor rotor. The savings in terms of time, money and smooth production were huge and paved way for future indigenisation efforts for all components based on this methodology.

References

Balance quality requirements of rigid rotors-Part-1 (1940), Determination of permissible residual unbalances, ISO Mechanical vibration.

837-6