METHODS AND PRACTICES TO INVESTIGATE THE FACTORS AFFECTING FAILURES IN TURBOCHARGER TURBINE: A REVIEW

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Abstract: The major components of a turbocharger are the compressor, bearing housing and turbine. In this paper, different types of failures which occur in turbine wheel are discussed and some remedies to reduce the failures are presented. It is seen that the High Cycle Fatigue (HCF) is a major cause for the failure of turbine wheel blades. The ways to predict HCF risk to failure and some of the practices to reduce them are also discussed. With the reduction in HCF risk of failure, the life of turbine wheel can be increased. At the earliest phase of design, it is necessary to analyze HCF phenomenon which makes the design of the turbine efficient, reliable and robust.

Index Terms: Turbocharger High Cycle Fatigue (HCF), Turbine efficiency, Fourier amplitude, CFD analysis.

I. INTRODUCTION

A turbocharger is a turbine-driven forced induction device that increases efficiency of an Internal Combustion (IC) engine and power output by forcing extra compressed air into the combustion chamber. This improvement in power output of a naturally aspirated engine is due to the fact that the compressor can force more air and thereby proportionately more fuel into the combustion chamber than atmospheric pressure alone. The turbocharger is used in typical on-road commercial vehicles such as truck, cars and off-road vehicles such as trains, construction equipment engines. They are used with CI engines i.e., diesel engine applications.

Major issue for car manufacturer according to some international regulations and the customer requirements for fuel consumption, is to manufacture efficient Compression Ignition (CI) engines to produce low carbon dioxide emissions. In order to reduce the emissions and to make the engine efficient, turbocharging of engine came into practice. Turbocharger helps in increasing the torque and power capability of CI engines. Turbocharging leads to engine downsizing and helps in reducing the emissions, etc.

Hence, nowadays a market for turbocharger demand is increasing because of its obvious advantages. Several auto-manufactures are turbocharging their vehicles. In order to be in this competitive market and satisfy customer's requirements with environmental regulations, research efforts have been focused on increasing the life or assessing the major factors of failures in turbine.

II. LITERATURE REVIEW

A literature review based on "selective citations" is carried out with a view, to identify the factors leading to the failures in turbocharger-turbine, to review the methods for analysis of such factors and the techniques and remedies used to reduce the effect of these factors. This review of literature includes the major factors which are leading to failures of turbine. There are several factors which are affecting the life of blades. In the past, various studies and investigations on these factors of failures have been carried out by several researchers.

Factors Affecting the Failures of Turbocharger Components and Remedies:

The researchers in the past have discussed various factors affecting the failure of turbine blades as corrosion failure; fretting fatigue; fatigue-creep failures etc. Corrosion failure occurs due to metal wear or oxidation due to chemical reactions. This type of failure is accelerated by warm temperatures, acids and salts. Low pressure and medium pressure turbine blades are more susceptible to this corrosion failure [1]*. Many researchers from fractography analysis have confirmed that the corrosion fatigue cracks are often initiated by inter-granular cracking of pits, beach marks and striations. Low pressure turbines generally fail due to crevice type corrosion which involves several pits/grooves formations at the edges of the blades. Corrosion affects structural reliability of the turbine blade since fatigue cracks can nucleate from corrosion pits and get accelerated. Gas turbines also show failures due pitting at leading and trailing edge of the blade surfaces. Initiation occurs due to hot corrosion at leading edges and propagated by fatigue [2]. Preventive measures such as advanced alloys and surface coatings for turbine blades have been suggested. Some of the recently developed methods like ion plating, plasma transfer arc welding, bronzing and hybrid coating can also be used for prevention [3]. Shot peening to release residual stresses is also a good method of building resistance against corrosion fatigue. Electroplating method is also suggested as a preventive measure for this type of failure. Fretting cracks are quite small and these may lead to severe damage of the blades. A complex interaction between High Cycle Fatigue (HCF) and Low Cycle fatigue (LCF) encounters the fretting fatigue [4]. Two predominant methods are suggested to reduce fretting fatigue failure. These are coatings and shot peening. Nitrogen ionic implantation with subsequent vacuum plasma coating deposition of titanium nitride is most prospective method to increase fretting resistance of titanium alloys [5]. By adopting several methods and techniques for investigations on high pressure turbine blades failures, it was observed that the major failure is due to HCF. Turbine blades are subjected to very high levels of stress and temperature during each operating cycle of engine. Due to transient load condition of engine and sharp corners in turbine, fluctuations are observed in the static pressure distribution around the wheel periphery. The blades of turbine wheel experience resonance in transient conditions, when the rotor accelerates or decelerates during start-up or shut-down operations and the blade passing frequency or its harmonics coincide with any of the natural frequencies of the blade. The effect of pressure fluctuations coming from the turbine housing can develop excessive vibratory stresses on turbine blade causing a fatigue fracture. Due to high dynamic stresses, blade vibrations and the occurrence of resonance lead to HCF failure. Fatigue fracture mainly develops near the trailing edge of the wheel blade. Hou et al. [6] employed a non-linear Finite Element Method (FEM) to determine the steady-state stresses and dynamic characteristics of the turbine blade. The steady-state stresses and dynamic characteristics of the blade were evaluated and synthesized in order to identify the cause of blade failures and a pre-stressed modal analysis was performed to examine the dynamic behavior of the blade and disc assembly under service conditions. From the analysis it was concluded that the first bending vibration mode was not a significant contributor to failure. The second vibration mode is a possible cause of fatigue because the maximum stress corresponding to this mode is coincident with the point of crack initiation. In order to reduce the risk of blade failures by HCF, certain design methodologies are opted. Probabilistic method approach is one such method available to designers to avoid high cycle fatigue failure. This method gives a better understanding of how the parameter change affects the response. Variation of values of design parameters changes the blade natural frequency and modal stress. Brown [7] presented a methodology based on probabilistic analysis to determine probability distributions of blade frequency and modal stress. In this case, the Monte Carlo sampling method was used. Each Monte Carlo iteration results in random blade geometry and modifies a MSC. Nastran data file, runs the solution, and stores the new frequency and modal stress values. The distribution of response gives the designer a broader understanding to decide what input variations are influential on response variation and the margin of system's capability.

Ibaraki et al. [8] conducted computational and experimental investigations on the turbine housing. Two different models of trapezoidal cross-sectional shape were analyzed for performance parameters under pulsating pressure conditions. While changing the cross-sectional shape, the precautions taken was that the area schedule of turbine housing is maintained same i.e., A/R ratio was maintained. Results show a stronger flow distortion in span wise direction at the rotor inlet with the baseline volute. From the experimental results and CFD results, it was observed that the swallowing capacity is hardly influenced by the cross-sectional shape. Higher pressure loss is generated due to sharp corners and flatter cross-sectional shape enhances the development of secondary flow.

Methods of CFD Simulation and Experimental Analysis

Several researchers have worked on methodologies to achieve better correlation of results of experimental analysis with the CFD simulation on radial turbines. Galindo et al. [9] presented a CFD method for simulating radial turbocharger turbine flow and validate it with experimental results. To simplify the analysis, the turbine was divided into different regions: volute, nozzles, rotor and outlet. Interfaces between the regions were used for post-processing. Heat transfer from turbine walls was considered to be adiabatic, steady flow conditions were considered based on standard procedure followed by manufacturers. Numerical stability and convergence in radial turbine simulations was good enough with total pressure and temperature at inlet and static pressure at outlet [10]. The simulation was carried out with multiple reference frames (MRF) with frozen rotor approach for wheel domain. Based on the literature survey of turbulence modeling, k-ω SST model with automatic wall functions for computation was considered because it showed good agreement between computational data and experimental data and even ensures high degree of grid independence. To achieve good relation and accurate results, a local mesh independent method was followed. For the tongue region of the volute, as shown in fig.1, this method was adopted to achieve good results in computation with different volute grids while keeping the rest housing domain to be of the same mesh. Based on the mass flow rate and percentage torque values with respect to mesh elements, final simulation mesh was selected. On the tongue edge, ANSYS-Fluent - centered size function was used. The size function was set to be the half of local mesh (default size) input parameters for tetrahedral grid and a growth ratio of 1.1 to achieve the mesh smoothening. In Robust Octree method, subdivisions are carried out until the size of the refined octants is on the order of the local edge lengths at the boundary surfaces [11].

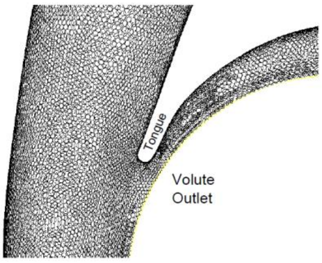

Fig-1: Volute tongue mesh [9]

J. Suhrmann et al. [12] discussed the methodology and geometrical features of a turbine to develop the radial turbine stage. Essential factors to decide the performance of turbine are expansion ratio (ER), rotational speed of wheel, mass flow rate and the turbine efficiency. Design of volute of turbine plays a major role in turbine stage since it defines mass flow parameter and absolute rotor inlet flow angle. The tongue portion of volute affects the overall circumferential rotor inlet flow angle because it generates non-uniformities in the flow. It is stated that from the point of thermodynamics, design of tongue should be sharp. However, due to constraints in manufacturing it is not possible. As turbine housing is having enormous high temperature environment it gives high thermo-mechanical loads on tongue area. These loads may develop a possible critical location of the crack. Also, manufacturing of tongue with these constraints is not possible since turbine housing is a casted part. The plots of Flow capacity, Efficiency and Blade excitation vs. tongue to wheel distance Δz (in percentage) were obtained as shown in fig.2.

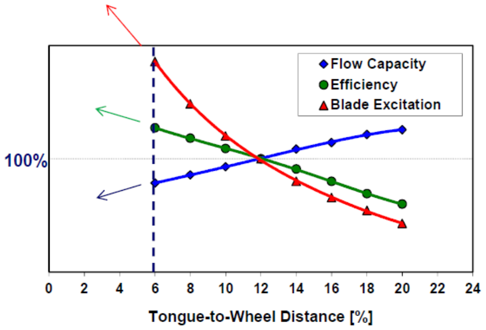

Fig-2: Performance parameters vs. Δz [12]

From fig-2, it is observed that the flow capacity increases with Δz, efficiency drops with increase in Δz and blade excitations increases with reducing the Δz. The impact of different design parameters on the flow conditions was investigated. Major focus of the research was near the tongue position since it produces non-uniformities in flow. To study the effect of the variation of these design parameters on the flow near the tongue location one may determine the number of experiments to be carried out using the technique of DOE. However it was found that the number of experiments to be carried out is large in number. To carry out this large number of experiments involves a very high cost. Hence numerical calculations were carried out and the results were presented. Two methodologies were used to get the results. In the first method (Case I), the turbine full stage parts were included and in the second method (case II) only the inlet duct and volute were used to make the geometry simplified and to get the solutions at a faster rate. Numerical boundary conditions given were constant and the steady state analysis was done. In Case I, geometrical change was implemented: Tongue radius was constant with respect to angular movement of tongue from 5 to 30 degrees and incase-2: Tongue radius was changed with respect to angular movement of tongue from 5 to 30 degrees. In case-1, the results obtained for stator loss coefficient with constant tongue radius and varying tongue angle are almost same and for case-2 the losses increase as the tongue angle is more than 10degrees. In both the cases the velocity ratio decreases with increasing the tongue angle. The results of simplified geometry with the full turbine stage model were validated. In addition to this, the amplitude of pressure fluctuation generated creates vibration on the turbine blades which leads to increase in the risk of HCF. So, it was suggested to operate turbine with maximum desired performance with a small tongue radius and with a small tongue angle. To make the turbine design robust in nature with low risk of HCF, a larger tongue distance (i.e., larger tongue angle) should be used.

S. Kitson, et al. [13] developed the CFD method and used to determine static pressure distribution around the turbine wheel periphery. A method to predict the blade strain distribution at the first mode frequency is also developed. The experimental results are compared with the CFD results. By having four tapings on the wheel hub (only hub without blades) each one of them at 90 degree, the static pressure distribution around the wheel periphery was measured. This pressure distribution helps in formulating the forcing functions of blade vibration.

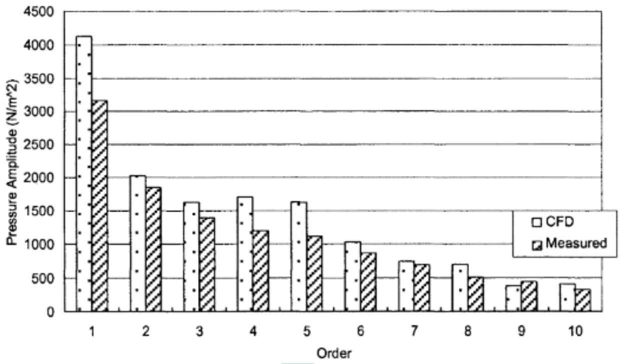

Fig-3: Experimental and CFD values of Fourier components [13]

In the CFD method, the time marching, explicit Reynolds Average Navier-Stokes (RANS) solver, unstructured tetrahedral mesh, k-epsilon turbulence model and semi-implicit residual smoothening have been used. The boundary conditions were taken from the test data. The waveform of pressure vs. time was transformed into the frequency domain via a fast Fourier transform (FFT) to extract the critical orders in Fourier components. It was observed that the values of Fourier components form experimental and CFD analysis are in fairly good agreement (fig-3). Using the method suggest by Kitson et al. one can develop a new turbine housing volute with a high level of confidence to optimize the pressure distribution around the wheel periphery.

III. MAJOR RESEARCH RESULTS FROM THE LITERATURE REVIEW

The turbochargers assume great importance in dealing with the problem of downsizing of engine with more power output than comparable naturally aspirated engine. Many researchers have shown in the research area of increasing desired turbine performance of turbocharger as well as the reliability of turbocharger.

Based on the “selected citations” of literature review, it is observed that the high performance turbine can fail in early stage due to corrosion, fretting-fatigue and fatigue-creep failures. Low pressure and medium pressure turbines are more susceptible to corrosion failure. Preventive measures like coatings and usage of advanced alloys are suggested. Fretting fatigue which is caused due to complex interaction of HCF and LCF can also be reduced by increasing the resistance of surfaces by shot peening or by nitrogen ionic implantation with plasma coating for titanium alloys. In high pressure turbines, the resonance occurs when any one of the natural frequencies of the turbine wheel blade coincides with the frequency of excitation. Due to this resonance, high vibratory stresses generated near the trailing edges of wheel blade may lead to failure. Hence, predominant failure in high pressure turbines is due to HCF. To assess this HCF failure, different approaches have been developed by the researchers.

Probabilistic method approach shows a better understanding of parameter change and its effect on the response. In order to have a better co-relation between simulation and experimental results many CFD simulation methods have also been presented by researchers. Current approach to lower the risk of failure due to HCF is to modify the existing volute geometry or to replace the existing design of volute with an improved one.

IV. RESEARCH GAP

From this literature review, it is observed that some efficient numerical methods have been presented to investigate the HCF failure risk in turbocharger turbine. However, there is a scope for developing a practical approach to reduce the Fourier components of static pressure fluctuations when these values of components are more than their critical values. It is also possible to develop different approaches to modify the existing assembly and geometrical configurations in volute design to reduce the Fourier components without affecting the desired turbine performance.

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