Using FEM and CFD for Engine Turbine Blades to Localize Critical Areas for Non Destructive Inspections

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***Abstract*— Damage to turbine blades is of critical importance in military aircraft engines. Irregular movements of throttle settings are a mandatory requirement for the pilots to perform various air combat maneuvers in military aircraft. It leads to excessive stresses on engine turbine blades in various flight regimes. The turbine blades are inspected exhaustively using non destructive inspection techniques during the engine overhaul process. A variety of non destructive inspections inspection methods like dye penetrant, eddy currents, magnetic particle testing and radiographic inspections etc are used consuming a large number of man machine hours increasing the cost of inspections. Still the possibilities of missing out internally damaged area due to micro cracks may also exist. Present research was focused on using Finite element methods (FEM) and/or Computational Fluid dynamics (CFD) to predict the location of possible damaged areas on turbine blades. These results could then be used as reference for carrying out non destructive inspections. In this manner the number of blades inspected by per unit time could be substantially increased leading to savings in inspection cost, lesser repair time and more focused fault isolation in the blades.**

***Keywords*—** Non Destructive Inspections, Finite Element Modeling, Computational Fluid Dynamics, HP and Turbine Inlet Temperature

I. INTRODUCTION

DAMAGE to turbine blades is of critical importance in military aircraft engines. The irregular movements of throttle settings are a mandatory requirement for the pilots to perform various air combat maneuvers. This leads to excessive stresses on engine compressor and turbine blades in various flight regimes. The aircraft are also required to fly in varying atmospheric conditions ranging from negative temperature in icing conditions to over 50 degree Celsius in summers. These factors in addition to operations from deserts and tropical weathers also add to the variety of conditions that a military aircraft engine is exposed. Three dimensional stress analyses of turbine blades were carried out to observe the regions of stress concentration [1]. The technique required preparation of silicon rubber molds to manufacture blade models through casting and photoelastic analysis was carried out to locate the areas of failures. The method was found to provide reliable stress concentration regions. Heat load and applied force influence on turbine blades was also investigated to carryout analysis of inlet temperature distortion through computational methods [2].

The temperature contours on a meridional mesh surface overlapping with Nozzle Guide vanes was observed and relationships for time averaged temperature at three span wise sections of rotor were established. The research show significant influence of heat and forcing on the blades. The leakage flow of combustion gas and air mixtures was observed to have severe influence on heat transfer rates to the blade tip of high pressure turbine [3]. It was observed cooling effectiveness to be highly dependent upon tip clearance on using computational and experimental techniques [4]. Turbine blade tips functional, design and durability issues were investigated based on blade tip aerodynamics, heat transfer and cooling. It was observed that nominal design conditions on blade tips could not remain constant because of degradation of blade tips over a period of time.

The local material loss on blade tips ultimately could alter the flow over tip and heat transfer coefficients resulting into further deterioration. Three dimensional Finite element stresses was carried out to simulation and optimize the design of a turbine disk/blade attachment [5]. Two dimensional analysis of certain regions were also carried out to economize the three dimensional analysis process because the 3-D analysis was taking nearly 50 times longer than the two dimensional processing to achieve an accurate estimation of stress distribution on the blades. Investigations into convection cooled high pressure turbine blades revealed that optimization of cooling, aerodynamics, stress and manufacturing requirements played a vital role in design of turbine blades [6]. Multidisciplinary optimization of internal cooling networks in turbine blades was carried out through computational techniques for F-100 Pratt and Whitney engine [7].

The design activity went through a number of manual design cycles proving the possibility of multidisciplinary design and optimization methodology to be a successful technique. It was proposed that a CFD solution could be used to predict external heat transfer coefficients. Design of turbine

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blades to withstand Turbine Inlet Temperatures (TIT) up to 2500 ^{0}F investigations were conducted using two and quasi three dimensional finite element heat transfer and stress analyses [8]. Heat transfer and stress analysis showed that life and efficiency requirements of high temperature resistant turbine blades required sufficiently cooled turbine rotor also. FEM was used to analyze the influence of bird strike on gas turbine engine fan blades [9]. The time step was closely related to the physical length scale of the smallest element on the model. A number of problems were resolved through use of High Power computing. To ensure that even small time steps could be considered for simulations.

The researchers were able to predict a successful use of this technique by observing that increasing initial impact velocity leading to an increase in maximum impact force and maximum plastic strain. FEM was also used successfully for stress calculations on turbine blades under the influence of centrifugal, thermal and aerodynamic loading [10]. An effort was made to correlate the life of blades with various types of cooling arrangements through use of FEM. It was observed that the presence of internal cooling passages did not result in significant change in blade stresses, nor in the magnitude and location of the highest blade stresses due to centrifugal loading. The main difference was caused due to thermal stresses. Nickel-base super alloys based turbine blades were investigated for creep strength and ductility [11].

It was observed that increased stress capability at fixed temperatures, increased temperature capability and life times could be achieved through these material considerations. The materials selections could improve the thermal fatigue resistance and higher blade and engine durability with improved performance. It was observed that CFD techniques were to not commonly being used as a design tool for locating the stress concentration areas through aerodynamic analysis [12]. Therefore an inverse method was used for investigating the turbine blades in viscous flow conditions. In this approach the fix wall boundary condition approach was replaced by the moving-wall boundary conditions.

The relationships were established for various loading and pressure distributions. The results showed that the inverse method of designing was capable of handling large separated flow regions a careful tailoring of target distribution could bring significant improvement in the results. Engine life, usage and cycle selection were investigated to establish the mechanical design requirements of gas turbine engines [13]. Typical strength requirements were based on the internal pressure, transmission of thrust force to airframe spread over a period of time. The engine duty cycle, required blade life and engine cycle selection were found to be related. Turbine inlet temperature and cooling airflow were the most critical factor influencing the life cycle requirements of the blades. FEM was used to model the actual bladed discs accurately for evaluation of fluid-structural coupling effects as investigated [14].

The approach was applied to industrial rotors which showed that aerodynamic coupling had significant influence on the vibration of bladed disks. Integrated lifing analysis for gas turbine components was investigated with the background that maintenance costs formed a major part of the aircraft cost [15]. It was observed that a significant reduction in these costs could be achieved through increasing the interval of these inspections and introducing the concepts of on-condition maintenance. The stress distribution was achieved through FEM analysis followed by lifing estimation of F100-PW-220 engine 3rd stage turbine rotor. The research was used to analyze the influence of engine deterioration of engine on blade life. CFD model for calculating the heat transfer to hot sections and FE models for calculating thermal and mechanical stresses were also used.

Considering the various methodologies used for estimating thermal and mechanical stresses on turbine blades, the authors were required to investigate the possibilities of using some of these techniques for the advantage of service technicians during overhaul cycle of aircraft engines. During overhaul a large number of non destructive inspections of blades were to be carried out on each turbine blade. It required very long inspection times leading to high cost as well as longer time for completion of the entire overhaul process. After careful consideration, it was envisaged that a combination of FEM and CFD could be used to establish the stress concentration areas in a typical turbine blade. These results could be given to service technicians as visual inspection work cards so that they could focus more attention to the stress concentration regions for any cracks or damage that may not be visible through naked eye. ATAR 09C engine HP turbine blades were therefore selected for such investigations. In the absence of exact geometry drawings, a blade 3-D geometry was required to be modeled followed by application of FEM and CFD for analysis.

II. MODELING OF BLADE GEOMETRY

Digital scanning is one of the methods being used in reverse engineering nowadays. It is basically a pre modeling step. The digital scan gives a point cloud of the shape of object to carryout full scale geometric modeling. The accuracy of model obtained from the digital scanning depends upon the number of data points of the cloud and are expected to be 98% accurate. The blade was initially cleaned chemically to give it the best shine. And then it was placed on the workbench of the scanner as shown in Fig. 1 (a) and (b) below:

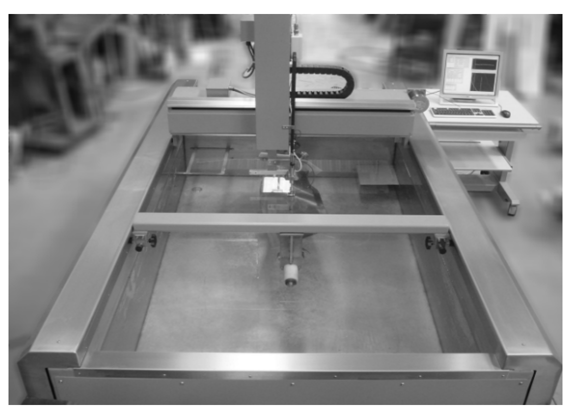

Fig. 1 (a) Turbine Blade located on the workbench of a digital scanner

Fig. 1 (b). Turbine Blade and digital scanner placed in dark room environment for best reflection through blade surface

The selected HP turbine blade (1st stage) was digitally scanned to get a point cloud of its geometry. Then this point cloud data was used for complete model generation of the blade. The process was reasonably time consuming and required careful consideration of scanned surface matching from face to face to achieve higher accuracy of the model. Point cloud data along with resultant shape of geometric model for turbine blade so achieved were as shown in Fig. 2:

III. FE APPLICATION ON TURBINE BLADE (STATIC ANALYSIS)

As learnt from the benefits of past research, FEM was chosen as the first technique to establish the stress concentration areas on the turbine blades. For this purpose, application of typical FE software (ANSYS version 11.0) was used.

The material properties including modulus of Elasticity as 250 GPA and Poisson's Ratio is 0.31of this blade were based on NKCD20ATU according to French standards (AFNOR) and commercial designation of Nimonic PK25. The same were assigned to the geometric model. A free mesh was generated over the volume using SOLID45 type element with plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities as shown in Fig. 3 and subsequently refined for any discontinuities.

The blade was constrained at the root in all directions. The net pressure force acting on the blade was applied in such a manner that the maximum pressure was near the quarter

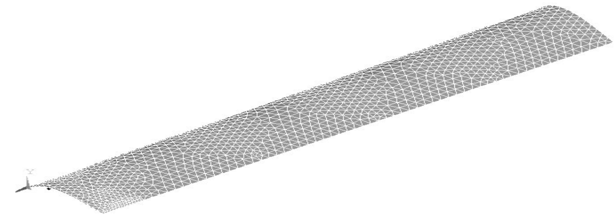

Fig. 3. 3-D Mesh generation over the turbine blade

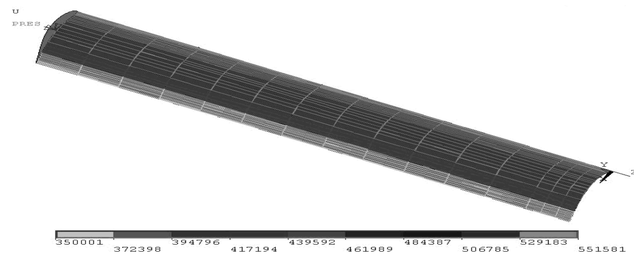

Fig. 4. Application of Pressure (Pa) on blade; lines show the applied pressure

chord of the blade aerofoil and gradually decreased away from quarter chord toward leading and trailing edges as shown in Fig. 4 .

The solution was obtained and results were obtained for displacements, stress and strain distributions over the complete geometry of blade.

A. Displacement on Path S at Leading Edge and Quarter Chord location

The results for displacements, over the complete geometry of blade are shown in following Fig. 5 (a), (b) and (c). Separate graphs were drawn for leading edge and quarter chord displacement values. As visible from Fig. 5 (b) and (c), the maximum displacement was at the blade tip and minimum at root. Apparently there was an exponential rise in the displacement from blade root to tip in both cases i.e. leading edge of the blade and quarter chord locations on the defined path. There was relatively small difference among the values of displacement at same location on the path for leading edge and quarter chord as shown in Table 1 below:

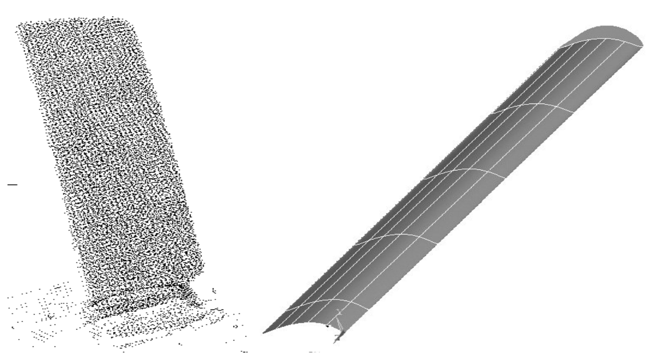

Fig. 2. Point Cloud data of Turbine Blade and resultant geometric model

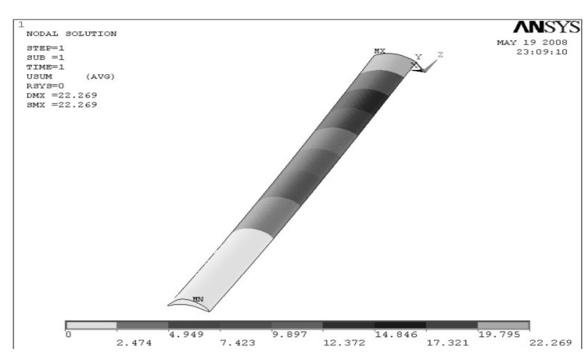

Fig. 5(a) Displacement results on Leading edge

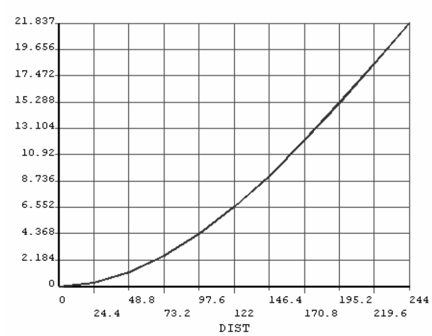

Fig. 5(b) Displacement results on Leading edge

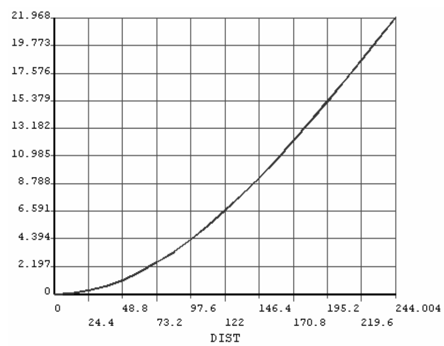

Fig. 5(c) Displacement results on Quarter chord

Displacement values were observed to be higher at leading edge from location 0 to 48.8 mm of blade length, became equal at 73.2mm. It then went on increasing at Quarter chord of blade until the blade tip. The deviation between the two values at the tip was observed to be only 0.6 % between leading edge and quarter chord.

The overall Maximum displacement value was observed to be 21.968mm at the blade tip. This displacement values was apparently high but was attributed to the fact that FE analysis was carried out while constraining the 6 Degrees of Freedom at the blade root, whereas in real life the blades are not completely constrained when installed on the turbine disk. This investigation however revealed the pattern of

Table 1: Comparison of Displacement at Leading Edge and Quarter Chord of Turbine Blades

Path Location S	Leading Edge	Quarter Chord
0	7.15E-12	0.60936E-11
24.4	0.32569	0.30201
48.8	1.1389	1.1297
73.2	2.507	2.507
97.6	4.3383	4.3587
122	6.5752	6.6179
146.4	9.185	9.246
170.8	12.098	12.182
195.2	15.236	15.338
219.6	18.511	18.63
244	21.837	21.968

displacement observed on the entire blade geometry when constrained at the root.

B. Von Misses Stress on Path S at Leading Edge and Quarter Chord location

The results for Von Misses Stresses, over the complete geometry of blade are shown in Fig. 6 (a), (b) and (c). Separate graphs were drawn for leading edge and quarter chord displacement values. As visible from Fig 6 (b), the maximum stress was at the blade root and minimum at blade tip. Apparently there was a decrease in the stress from blade root to tip in case of leading edge of the blade. However at quarter chord locations the stress initially decreased and then started to increase along the path and started decreasing again on the defined path. There was significant difference among the values of stresses at same location on the path for leading edge and quarter chord as shown in Table 1.

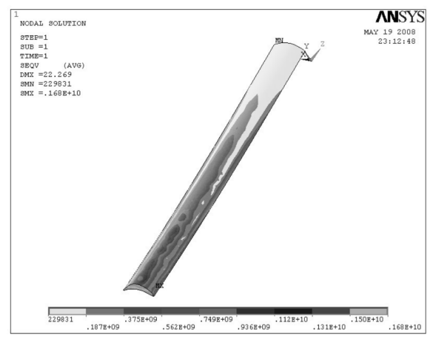

Fig. 6 (a). Von Misses stresses at Leading edge on specified path

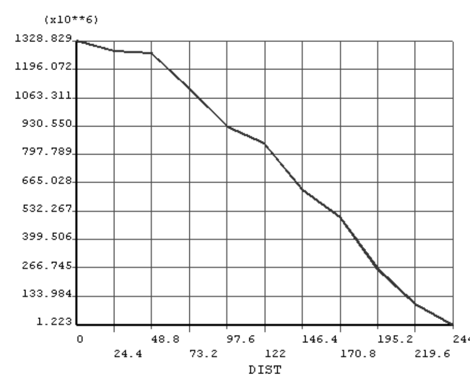

Fig. 6 (b). Von Misses stresses at Leading edge on specified path

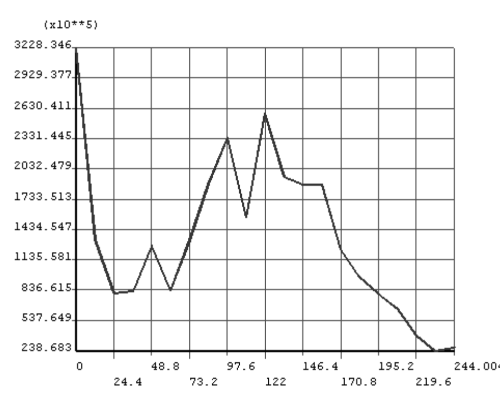

Fig. 6 (c). Von Misses Stress on quarter chord

Table 2: Von Misses Stress values

Path Location S	Leading Edge	Quarter Chord
0	1.33E+09	3.23E+08
24.4	1.28E+09	8.06E+07
48.8	1.27E+09	1.27E+08
73.2	1.11E+09	1.33E+08
97.6	9.29E+08	2.34E+08
122	8.48E+08	2.58E+08
146.4	6.30E+08	1.87E+08
170.8	5.06E+08	1.24E+08
195.2	2.61E+08	7.99E+07
219.6	9.50E+07	3.88E+07
244	1.22E+06	2.70E+07

C. Von Misses Strain on Path S at Leading Edge and Quarter Chord location

The results for Von Misses Strains, over the complete geometry of blade are shown in Fig. 7 (a), (b) and (c). Separate graphs were drawn for leading edge and quarter chord strain values. As visible from Fig. 7 (b), the maximum strain was at the blade root and minimum at blade tip. Apparently there was a gradual decrease in the strain from blade root to tip in both cases i.e. leading edge of the blade and quarter chord locations on the defined path. There was significant difference among the values of strains at same location on the path for leading edge and quarter chord as shown in Table 3.

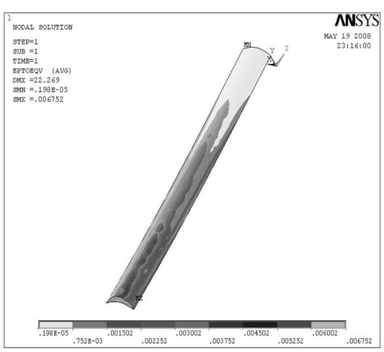

Fig. 7 (a). Von misses strain distribution on blade and graphical representation at leading edge

IV. COMPUTATIONAL FLUID DYNAMIC ANALYSIS

The turbine blades normally undergo excessive air pressure as well as thermal loading. Therefore, the structural analysis on the basis of load application may not be sufficient to explain the stress distribution over it. CFD technique provides answer to such a situation. The present investigation was based on application of pressure loads and thermal loading resulting from high pressure. The geometric data for the blade was collected through scanning technique.

The geometry was imported from ANSYS and Grid was generated using a software Grid-Gen. The negative values of Jacobion matrices obtained in Grid-Gen indicated that follow will converge over this grid. Then, the grid was imported to another software FLUENT and grid check was again performed. A steady state analysis is performed with implicit formulation in FLUENT and coupled solver is utilized for this purpose.

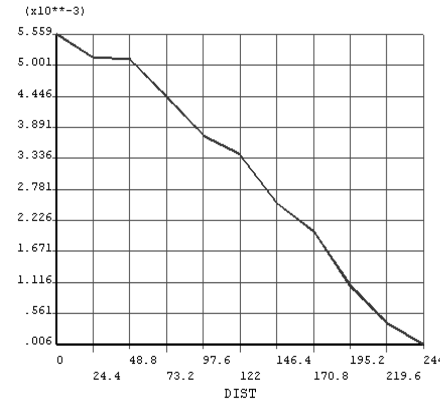

Fig. 7 (b). Von misses strain distribution on blade and graphical representation at leading edge

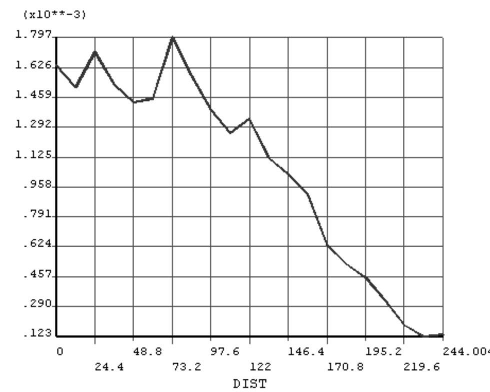

Fig. 7 (c). Von Misses strain at Quarter Chord location

Table 3: Von Misses Strain on blade

Path Location S	Leading Edge	Quarter Chord
0	5.56E-03	1.64E-03
24.4	5.14E-03	1.71E-03
48.8	5.11E-03	1.43E-03
73.2	4.44E-03	1.80E-03
97.6	3.75E-03	1.39E-03
122	3.40E-03	1.34E-03
146.4	2.53E-03	1.03E-03
170.8	2.04E-03	6.38E-04
195.2	1.05E-03	4.52E-04
219.6	3.83E-04	1.86E-04
244	6.31E-06	1.33E-04

A. Grid Generation through GridGen

The two basic requirements considered for CFD analysis of turbine blades were as follows:

- Distribution of mesh points may accurately reflect the geometric properties of domain boundaries.
- Distribution of points is sufficient to represent all physical features.

The type of grid used here to mesh complex geometry was unstructured grid. The model of blade was imported in the GridGen to create mesh over the surface of blade for CFD analysis. Far field was created in upper, lower, span, rearward and forward direction. Here the total number of Grid points was 860567 i.e. over 0.86 Million, Fig. 8. Root section was attached to symmetric plane. Special shapes of meshing regions were used according to the expectations of flow behavior like round shape mesh at Leading Edge (LE) because flow disturbance was too low in that region and huge disturbance in flow at and after LE so meshing region was bigger and of rectangular shape. The above far field was exported to the FLUENT after setting boundary conditions. The blade was set as wall, the domains outside the far field were set as pressure far field and a symmetric plane was at the root section of the blade.

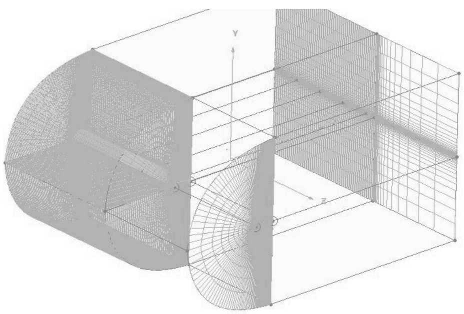

Fig. 8. Grid generated in GridGen

- Solution of Flow Equations around the Turbine Blade

Euler and Navier Stokes equations that govern the flow of gases and liquids were formulated on the basis of a continuum assumption. The calculations were performed over a collection of discrete points or elements. The computational domain was 3D space in which flow was to be computed.

B. Results Obtained from FLUENT

The following Fig. 9 (a), (b) show the model and grid imported in Fluent for CFD analysis. The distribution of grid in circular form with higher number of grid points in front of the blade model ensured higher accuracy of results. Fig. 9 (a) shows blade grid attached to root is symmetry at both ends of the blade as seen in Fig. 9 (b). For the purposes of analysis airflow with its standard properties was selected. The actual flow parameters selected were as follows:

- *Actual parameters for Flow*

Pressure = 5.6 MPa, Chord = 0.036 m; Temperature = 3023 K;
Reynolds No. at this temp = 2.355×10^5; Velocity = 771.475 m/s;
Viscosity = 7.73×10^{-5}, Speed of sound = 1102.1 m/s;
Mach No. = 0.7 Density= 0.6556 kg/cubic meter

The formulated flow parameters for using in fluent were as follows based don Reynold's No. computed above. Since Reynolds no. and Mach no. was same for both actual and formulated flow for fluent, so both were assumed same:

- *Parameters for Formulated Flow for Fluent*

Pressure = 1.01 MPa; Chord = 3.6m from GridGen;
Temperature = 300 K, Reynold No. at this temp = 2.355×10^5;
Velocity = 243.03 m/s; Speed of sound = 347.18 m/s;
Viscosity = 4.37×10^{-7} m/s Mach No. = 0.7; Density= 1.768 kg/m^3

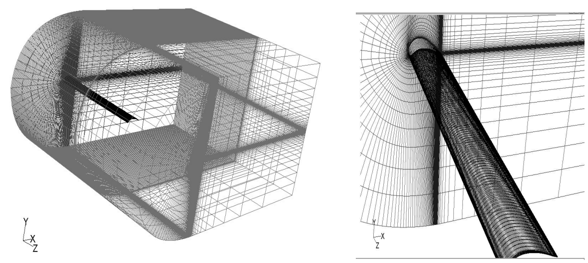

Fig. 9. (a), (b) Grid in FLUENT

One would notice from Fig. 10 (a) and (b) that maximum pressure values are observed at the blade leading edge root and blade trailing edge tip. Therefore these regions will have the highest probability of developing cracks. A service technician must therefore conduct very meticulous inspection at these two regions to ensure that cracks are not missed out.

Total pressure and static pressure distribution in the domain was also observed as shown in Fig. 10 (c) and (d) below. Temperature distribution over the blade as a result of applied pressure distribution resulted into thermal loading over the blade geometry. This in real time would add to the overall stresses, a blade is being exposed to. The graphic representation for static and total temperature over the blade as shown in Fig. 11 (a) indicates that the blade has the highest values of temperature near the blade tip and temperature distribution values are also shown in Fig. 11 (b).

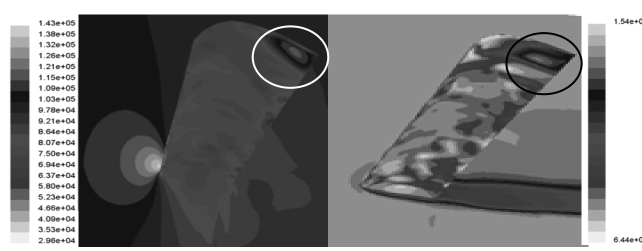

Fig. 10. (a), (b) CFD results of pressure loading for static and total pressure

Based on these results it could be predicted that high temperatures at blade tip are likely to add to the development of cracks and may be considered as a critical region by the technicians for crack detection inspections.

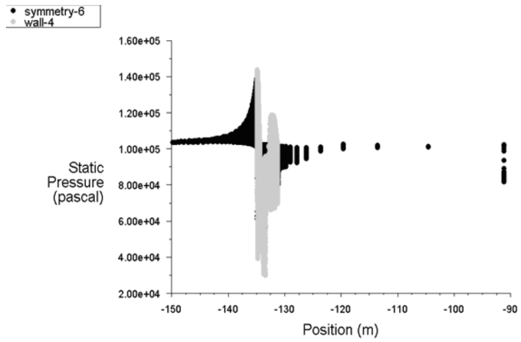

Fig. 10 (c). Static pressure distribution

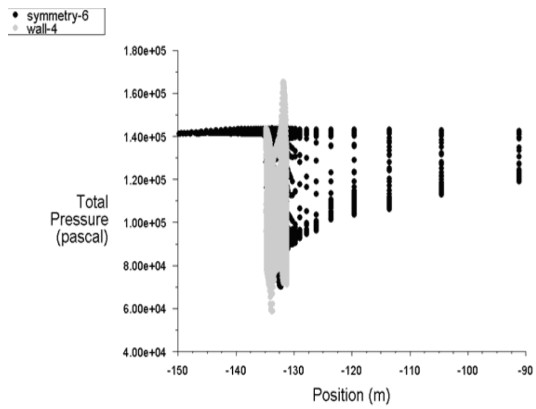

Fig. 10 (d). Total pressure distribution

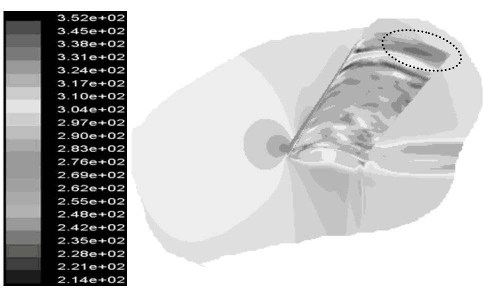

Fig. 11 (a) Highest value of temperature at encircled region and variation of temperature on turbine blade

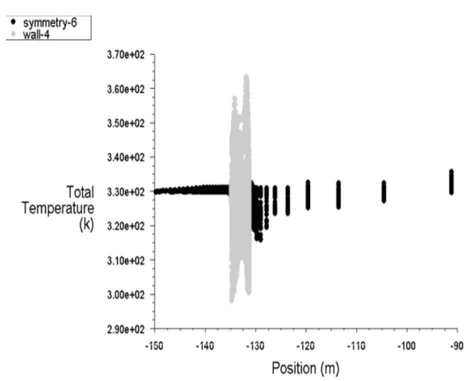

Fig. 11 (b) Highest value of temperature at encircled region and variation of temperature on turbine blade

V. NON DESTRUCTIVE INSPECTIONS

A host of NDI techniques are available to aircraft industry for determination of cracked locations in actual blades and to ensure that any deterioration caused by service conditions is detected. Out of 72 known NDI techniques, the 5 were utilized for crack location analysis of turbine blades. In Visual Testing method, the enlargement of major cracks, x3 to x6 magnifying lens (single & compound) are used for visual inspections. In this technique simply the major cracks become visible with the help of these magnifying lenses. Penetrant Testing technique utilized florescent penetrants and visible dyes to locate the medium size cracks on turbine blades. Heated filament, as cathode, helps electrons to accelerate by high voltage in radiographic testing method and X-rays are produced in the process which strikes a tungsten target, copper as anode, in a vacuum tube. Magnetic Particle Testing, Ultrasonic Testing and Eddy Current Methods were also applied to turbine blades and locations of defects on these blades were marked.
The most common defects observe during these inspections are shown in Fig. 12 (a), (b) below:

VI. COMPARATIVE ANALYSIS OF ACTUAL AND SIMULATED RESULTS

A careful analysis of actual cracks observed through NDI and computational techniques used for simulations provide a confirmation and correctness of FEM and CFD predictions of stress concentration areas. These areas could act as initiating locations for cracks due to pressure and thermal loading on the blade.

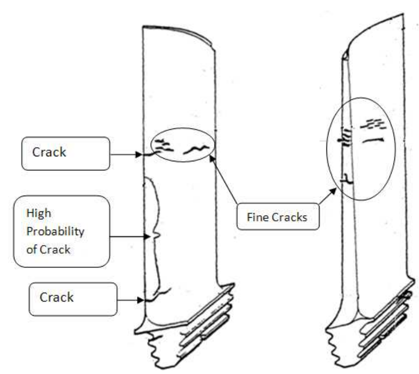

Fig. 12(a). Cracks observed in blades through various NDI techniques

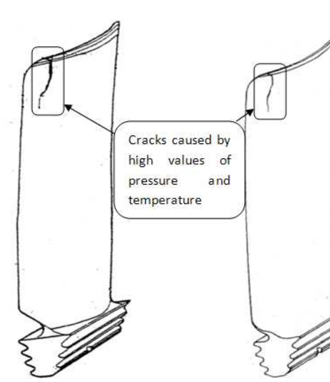

Fig. 12(b). Cracks observed in blades through various NDI techniques

A review of results from FEM analysis in Table 2 showed that higher stress values were observed at leading edge being maximum towards root of the blade. However on quarter chord locations, maximum stress values were observed at root then decreased towards middle of blade and there was a sharp rise at path location S= 97.6 the value went sharply high as in Fig. 6(c). it decreased slightly and then went to an even higher value at S=122. While comparing these values with actual blade inspection results through NDI in Fig. 12 (a), one could notice that there was a significant no. of cracks at the mid location of blades at the leading edge and quarter chord locations. Cracks were also observed at trailing edge of blade which could be attributed to high stress values over smaller thicknesses of trailing edge. These facts confirmed the successful utilization for FEM analysis using Ansys for prediction of crack locations on turbine blades.

CFD analysis using Fluent had shown that maximum stress concentration could be observed at trailing edge of turbine blades towards blade tip as shown in Fig. 10 (a) and (b) due to high pressure loading and high thermal stress values at same locations as in Fig. 11 (a). The NDI inspections of blades showed the existence of cracks towards tip on trailing edge of blade as shown in Fig. 12 (b). These results confirmed that CFD analysis could be used successfully for prediction of cracks on turbine blades at different locations. The results so collected could be used by service technicians as a reference for NDI inspections.

VII. FINDINGS

Present research was based on using Ansys and Fluent software for structural and computational fluid dynamic analysis of turbine blades respectively. Extensive simulations resulted into following major findings:

A. Maximum deflection on turbine blades was observed near its tip and the least values were observed at the root. A polynomial relation was observed for this increased in displacement from root to tip. On actual turbine these displacements are controlled through the serrated root design of the blade with a specific value of play in its attachment to rotor disc.
B. Von Misses stress stresses were observed highest at root and decreased towards tip at leading edge of the blades which could be approximated through a linear relationship with reference to location on the leading edge. However at quarter chord the stress value was observed highest at blade root. It decreased along the selected path till middle of blade and sharply increased at a middle region. It decreased again when moved away towards tip of the blade. Von Misses strains were also observed to be decreasing from root to tip.
C. A significant difference in Von Misses stress was observed between leading edge and quarter chord showing a decrease at all locations on quarter chord.
D. Total and static pressure and temperature values were observed as maximum at blade tip through CFD analysis which could contribute to cracks initiation at or near those locations.
E. NDI analysis of turbine blades showed existence of cracks at the trailing edge as well as leading edge near blade root, middle locations of the blade at both leading and trailing edges and tip of blade towards trailing edge.

VIII. CONCLUSIONS

Present investigation was focused on evaluating the possibilities of using FEM and CFD analysis for prediction of regions of crack location on aircraft engine turbine blades. The simulation results were compared with actual blades inspected through NDI. The crack locations predicted through the two simulation methods had close approximation with the actual results. It also confirmed that these techniques could provide guidance to service technicians for more having a closer look at the regions predicted through simulations to ensure that cracks are not missed. The results of simulations provided to service personnel in form of inspection job cards providing visual locations of stress concentration areas could also help increase their efficiency and expedite inspection processes. This could ultimately lead to maintenance cost reductions of aircraft engine overhaul and inspection processes.

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