Transient Thermal Analysis of Aero Engine Static Structures

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Abstract

Advanced gas turbines used for present day military aircrafts require higher thrust and lower specific fuel consumption. The thrust of the gas turbine engine can be increased by increasing the turbine entry gas temperature. The specific fuel consumption can be reduced by increasing the component efficiency. Compressor and turbine are the major components of the gas turbine engine. The relative movements that exist between rotor and stator components are responsible for varying tip clearance. The temperature prediction of the static structure and rotating parts is a vital input for estimation of clearances. This contradicting requirement of the tip clearance makes it important for estimation of static structure temperature. Hence this article deals with estimation of steady state and transient thermal responses of complete static structures such as fan casing, compressor casing, combustor casing and turbine casing. The casing temperatures are measured during engine test with help of thermocouples. Validation of temperature prediction for combustor casing has been carried out at steady state and transient cycle at three locations. There is good agreement between the measurements and predictions for both steady state and transient condition. Study of thermal response during steady state and transient analysis has done and observed that thermal response at rotor section is more compared to stator section and also difference between steady state temperature and transient temperature is less at rotor section. Parametric analysis carried out to study the effects of casing temperatures by varying heat transfer co-efficient on gas side and coolant side and temperatures on gas side and coolant side and the study shows that gas temperature is affecting more compared to other parameters.

Keywords: Tip clearance, thermal response, steady state, transient

I. INTRODUCTION

Developments in analytical and experimental approaches in aerodynamics have improved the compressor and turbine efficiencies up to 90% and further developments will be challenging. Further improvement in designs will have to concentrate very wisely on features such as reduced tip leakage flows and particularly tight clearances throughout flight cycle.

Harish Agarwal and Srikanth Akkaram (2008) stated that gas turbine blade tip clearances need to be optimized to improve engine efficiency, because excess clearance during operation at the aero foil tips leads to performance loss hence it must be kept minimum . A tight build clearance will lead to rubbing between casing and rotor during start up and shut down. Therefore a well-adjusted design is required to provide tight operating clearances and avoids excessive rubs during transient events and operation at off design conditions.

There is a large growth prediction during start-up of engine in the rotor model; this is mainly because of the fact that the mechanical growth of rotor is dominant during start-up.

In stator growth model, growth of stator depends upon thermal and mechanical loads. The growth of the stator can be described as

$$D_{casing\ (t)} = D_{mechcasing\ (t)} + D_{thermalcasing\ (t)}$$

Casing growth due to mechanical loading will be negligible and total growth will depend only upon thermal loads.

B. Lattime and Bruce M. Steinetz (2002) given that improved sealing in both HPC and HPT can provide reductions in specific fuel consumption, engine efficiency as well as increased payload and mission range capabilities. They also discussed about engine thermal state that is Engine temperatures play a massive role in determining operational clearances. The take-off pinch point will be very much lesser for hot engines in contrast with cold start engines because rotor is larger due to its greater thermal mass as compared to the case, thus proper cooling time is generally allotted before an aircraft can take-off with hot engines.

P. Pilidis and N.R.L.Maccalum (1984) has given that variations in tip clearance affects changes in component efficiencies, this can be considered as indirect effect of heat transfer, even though tip clearances are also altered by centrifugal and pressure effects. With regard to static structures inner and outer surfaces are subjected to gases at differing temperatures and pressures moving with different velocities. They also cited that only mechanical loading considered is pressure change for casing and also its effect will be very small, about one percent of total movement of rotor due to mechanical effects.

Alexander N. Arkhipov (2009) has given that it is necessary to develop combination of 2D/3D analysis for axial and radial clearance assessment during engine operation. For heavy duty gas turbine efficiency it is important to evaluate the blading clearance at the design stage. The minimum clearance value at base load is restricted by pinch point clearance during start up or shut down. Therefore transient analysis is necessary for different operating conditions.

The temperature prediction of the static structures and rotating parts is a vital input for estimation of thermal growth and also to maintain optimum clearances throughout engine cycle. The running clearances during the transient are also important to assess the cold clearances during assembly of engine components. Hence the prediction of casing temperature is important to evaluate the thermal growth of casings accurately. This contradicting requirement of the tip clearance makes it important for estimation of static structure temperature.

II. PROCEDURE

Static structures forms major portion of gas turbine which includes fan casing, compressor casing, combustor casing and turbine casing. Casing structures are complex with inner and outer surfaces of casing subjected to gases at different temperatures and pressures also moving with different velocities. Since Casing growth will be dependent only upon thermal loads. Steady state and transient thermal analysis of static structures has been carried out.

2D Modelling of aero engine static structures such as fan casing, compressor casing, combustor casing and turbine casing has been carried out and meshing has done using Hypermesh V12. Steady state and transient analysis has done using Ansys 16 software. Ansys is finite element software which can handle thermal, structural etc.

A. ANSYS Modelling

A finite element based software ANSYS which gives good results is used for the analysis. PLANE-55 element is used for thermal analysis. Plane 55 can be used as plane element with 2-D thermal conduction capability. The element has single degree of freedom, temperature at each of its four nodes. The element can be applied to 2-D, steady state or transient thermal analysis. Materials used for casing are nickel based alloys; their corresponding non-linear material properties are used for analysis.

Figure 1, Figure 2 and Figure 3 shows the meshed models of fan casing, compressor combustor casing and turbine casing respectively. The models are meshed using Plane 55 elements.

Fan casing model consists of 53,857 nodes and 51,167 elements. Fan casing model having maximum aspect ratio of 3.55 and minimum jacobian of 0.42

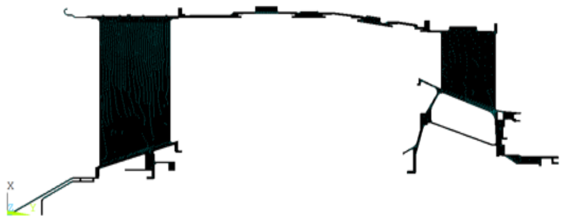

Figure 1: Finite element model of fan casing

Compressor combustor model consists of 42,568 nodes and 36,452 elements, having aspect ratio of 6.32 and minimum jacobian of 0.44

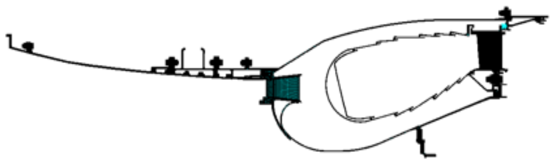

Figure 2: Finite element model of compressor combustor casing

Turbine casing and exhaust strut model consists of 47,822 nodes and 43,937 elements, having maximum aspect ratio of 5.29 and minimum jacobian of 0.49

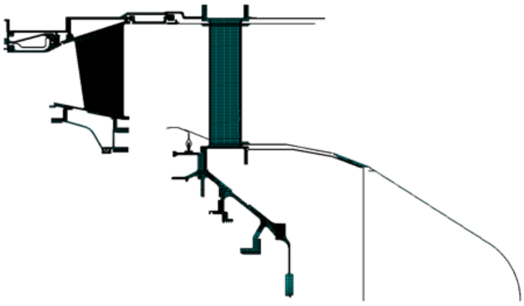

Figure 3: Finite element model of turbine casing and exhaust strut

The aerodynamic data from the different components of aero engine is used for estimation of heat loads using different correlations mentioned below.

Flat plate correlation $Nu = 0.0366 * Re^{0.8} * Pr^{0.33}$

Dittus-boelter $Nu = 0.023 * Re^{0.8} * Pr^{0.33}$

On vertical side $Nu = 0.02024 * Re^{0.8}$

On Horizontal side $Nu = 0.13 * Ra^{\frac{1}{3}}$

Tip clearance $Nu = 0.052 * Re^{0.8} * (1 - 2 * \left(\frac{Tc}{Bh}\right)^{0.8})$

B. Steady state and Transient thermal analysis

Steady state analysis is carried out for five different steady state conditions by imposing calculated heat loads on casings and corresponding nodal temperatures are estimated.

Transient thermal analysis carried out for mission cycle duration of 1784 seconds. This cycle consists of steady state dwells, acceleration dwells and deceleration dwells. Each dwell time is divided into 100 equal time steps in order to study transient response from one steady state to next steady state.

The mission cycle schedule followed for transient analysis shown in Figure 4.

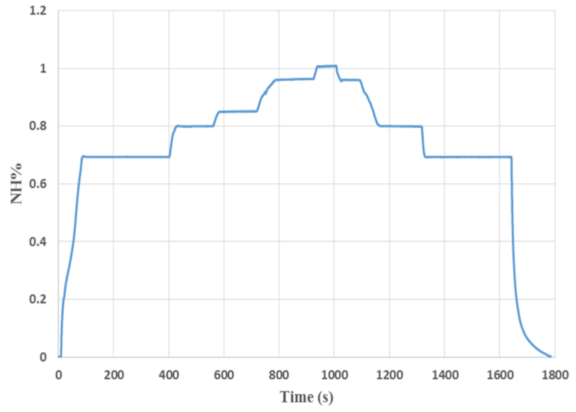

Figure 4: Mission cycle schedule considered for Transient analysis

From mission cycle time steps are calculated for transient analysis. Time step considered for transient analysis given below.

Table 1: Time step considered for transient analysis

Sr No	NH %	Time (s)	Activity	Dwell time	Time step
0	0	0		0	
1	0	9	0 to 1	9	**0.5**
2	0.7	93	1 to 2	84	**0.84**
3	0.7	403	2 to 3	310	**3.1**
4	0.8	431	3 to 4	28	**0.28**
5	0.8	562	4 to 5	131	**1.31**
6	0.85	587	5 to 6	25	**0.25**
7	0.85	720	6 to 7	133	**1.33**
8	0.96	789	7 to 8	69	**0.69**
9	0.96	926	8 to 9	137	**1.37**
10	0.1	942	9 to 10	16	**0.16**
11	0.1	1008	10 to 11	66	**0.66**
12	0.96	1026	11 to 12	18	**0.18**
13	0.96	1096	12 to13	70	**0.7**
14	0.8	1162	13 to 14	66	**0.66**
15	0.8	1318	14 to 15	156	**1.56**
16	0.7	1330	15 to 16	12	**0.12**
17	0.7	1642	16 to 17	312	**3.12**
18	0	1784	17 to 18	142	**1.42**

III. RESULTS AND DISCUSSION

A. Steady state thermal analysis:

Steady state thermal analysis carried out for different steady state conditions to obtain thermal contours. Non-dimensionalised temperature contours at peak condition for fan casing, compressor combustor casing, turbine casing and exhaust strut are given in Figure 5, Figure 6 and Figure 7. The temperature of fan casing is in range of 296K-439K, compressor & combustor casing is in range of 431K-1165K, turbine casing and exhaust strut is in range of 409K-1045K.

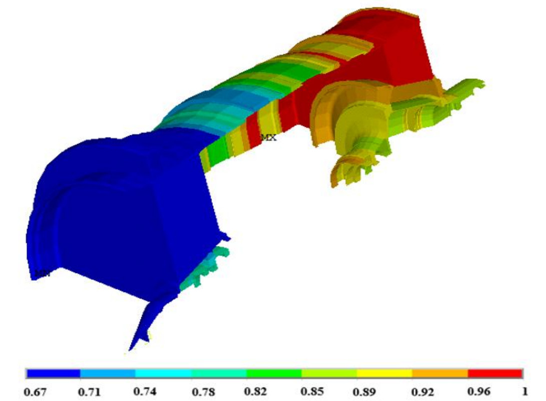

Figure 5: Non-dimensionalised temperature contour of fan casing

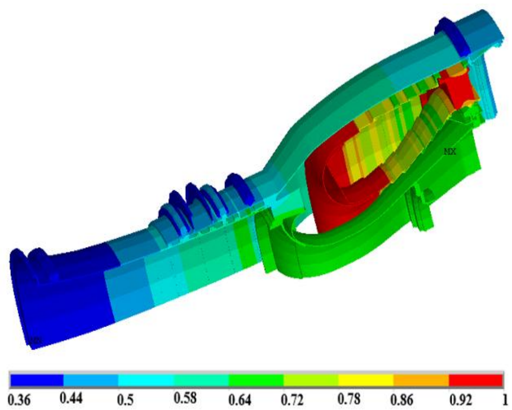

Figure 6: Non-dimensionalised temperature contour of compressor combustor casing

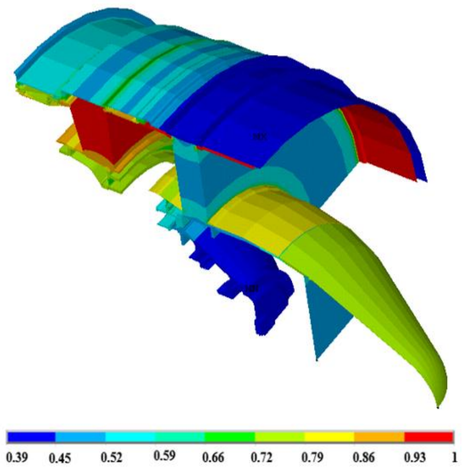

Figure 7: Non-dimensionalised temperature contour of turbine casing and exhaust strut

B. Comparison of temperature estimates with measurements

The casing temperatures are measured during engine test with help of thermocouples. The thermocouples are placed at three different locations on combustor casing with nomenclature 2EM, 3CM and 2CM. Figure 8 shows the thermocouple locations for combustor casing during engine run. The measured thermal responses are compared with estimated temperatures for the same transient cycle. Estimated thermal response is matching with measured thermal response at 2EM, 3CM and 2CM locations shown in Figure 9, Figure 10 and Figure 11 respectively.

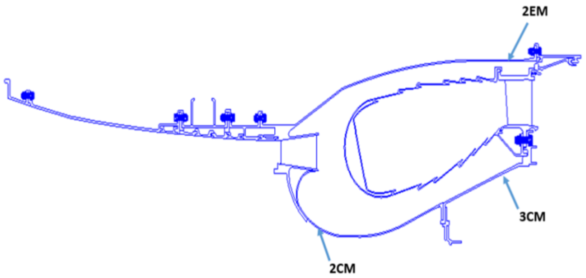

Figure 8: Thermocouple locations of combustor casing

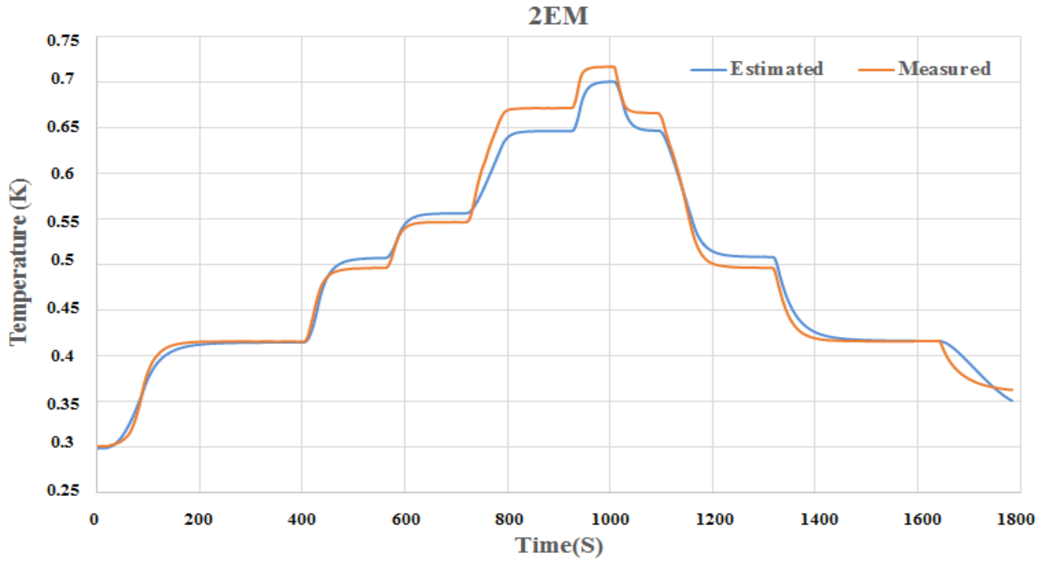

Figure 9: Thermal response v/s time for estimated & measured values at 2EM

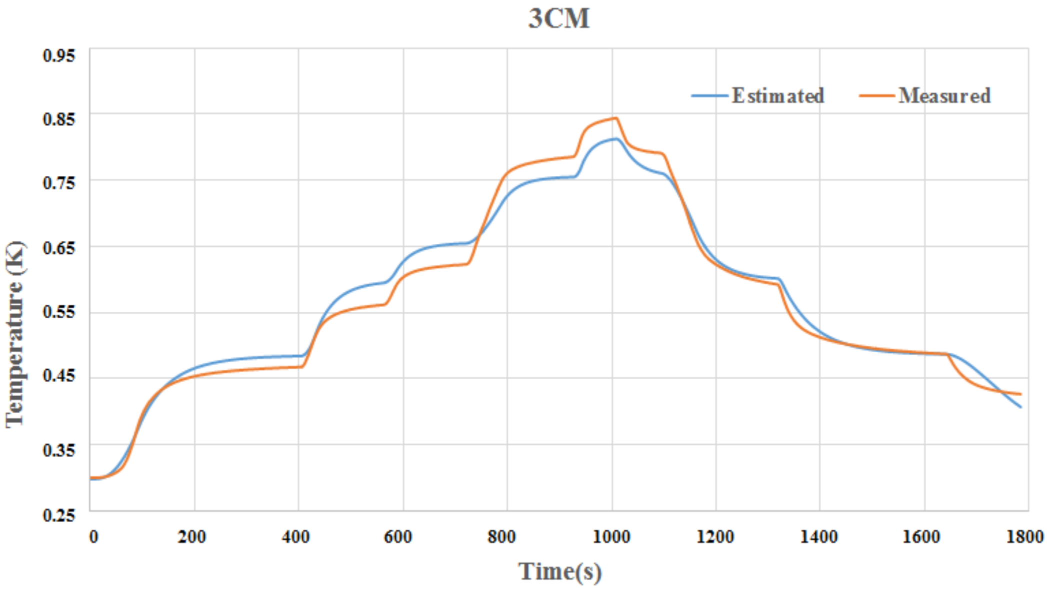

Figure 10: Thermal response v/s time for estimated & measured values at 3CM

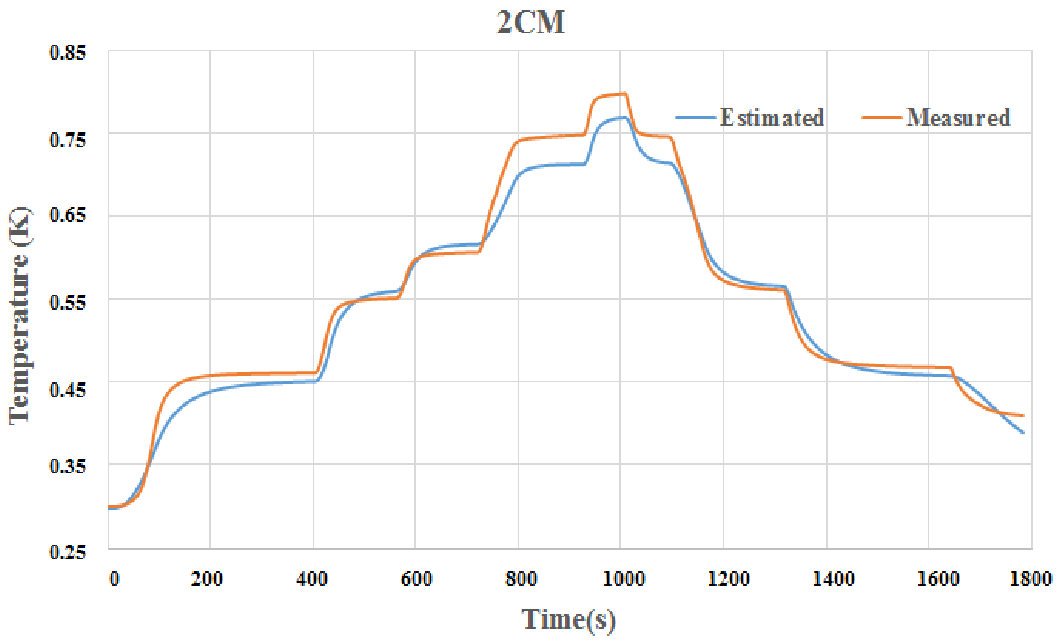

Figure 11: Thermal response v/s time for estimated & measured values at 2CM

Transient thermal analysis carried out for a typical transient cycle and the estimates are compared with measurements. Figure 9, Figure 10 and Figure 11 shows the variation of measured and estimated temperature during transient cycle at location 2EM, 2CM, 3CM respectively. The estimates are within 5% of the measurement data at locations measured during the engine run. The temperature difference between measured and estimated are shown in Table 2, Table 3 and Table 4 for the locations 2EM, 2CM and 3CM are given below.

Table 2: Comparison between estimated and measured data at 2EM location

NH%	Estimated temperature, K	Measured temperature, K	Difference, $T_{Estimated} - T_{Measured}$, K
0.69	414	415	1
0.8	506	496	10
0.85	555	545	10
0.96	645	670	25
0.1	700	715	15

Table 3: Comparison between estimated and measured data at 3CM location

NH%	Estimated temperature, K	Measured temperature, K	Difference, $T_{Estimated} - T_{Measured}$, K
0.69	482	465	17
0.8	590	560	30
0.85	654	625	29
0.96	754	780	26
0.1	812	838	26

Table 4: Comparison between estimated and measured data at 2CM location

NH%	Estimated temperature, K	Measured temperature, K	Difference, $T_{Estimated} - T_{Measured}$, K
0.69	450	460	10
0.8	555	550	5
0.85	615	605	10
0.96	712	745	33
0.1	768	795	27

C. Study of nodal thermal response during steady and transient analysis

To study the effect of transient analysis of static structures few nodes have been selected near to rotor and stator section. Figure 12 shows stator and rotor locations on fan casing. Steady state temperatures are plotted along with transient temperature as shown in Figure 13 (a) and Figure 13(b) at stator and rotor section. It is observed from graph that the difference between the steady and transient is less. Transient response at rotor section is more compared to stator section. It is observed that there is temperature difference of 20K at stator section and 5K at rotor section.

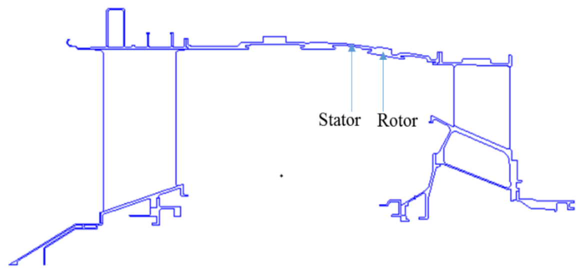

Figure 12: Locations considered at rotor and stator on fan casing

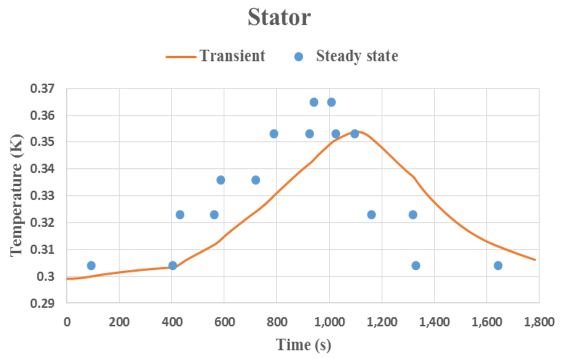

Figure 13(a): Comparison between steady and transient temperature of fan casing at stator

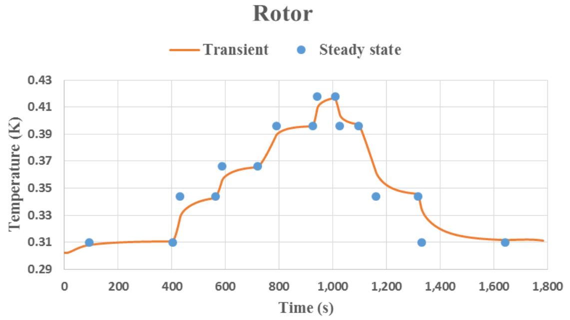

Figure 13(b): Comparison between steady and transient temperature of fan casing at rotor

Figure 14 shows the nodal locations considered on HPC casing at rotor and stator positions. Steady state temperatures are plotted along with transient temperature as shown in Figure 15 (a) and Figure (b) at rotor and stator section. From the graph it is observed that there is temperature difference of 30K at rotor section and 50K at stator section between steady state and transient temperatures.

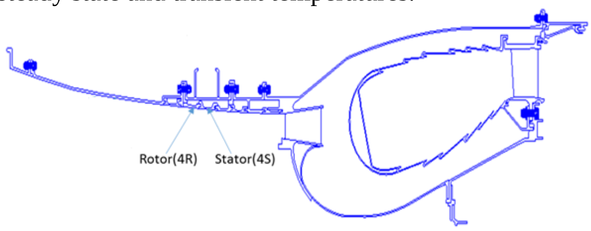

Figure 14: Locations considered at rotor and stator on HPC casing

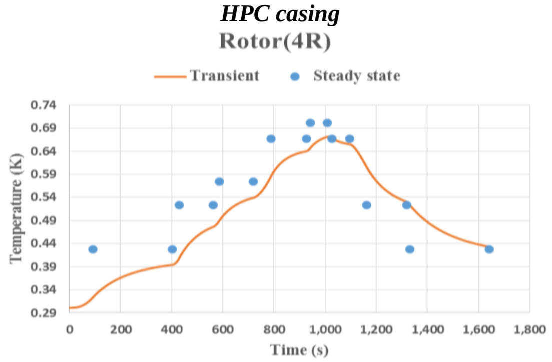

Figure 15 (a): Comparison between steady and transient temperature of HPC casing at rotor

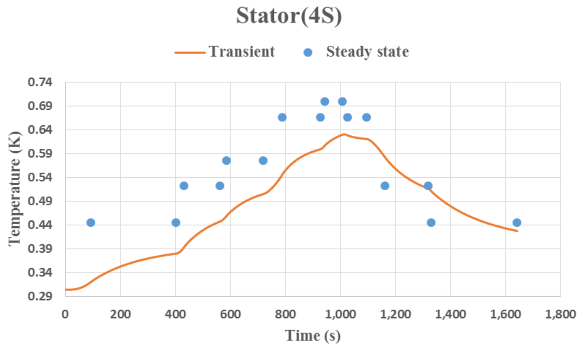

Figure 15 (b): Comparison between steady and transient temperature of HPC casing at stator

Figure 16 shows nodal locations chosen on turbine casing and strut. Nodes are considered on gas side and coolant side at LPR tip location. It is seen clearly from Figure 17 (a) and Figure 17 (b) that on gas side transient response is same as steady state response whereas towards coolant side there is variation of 5K.

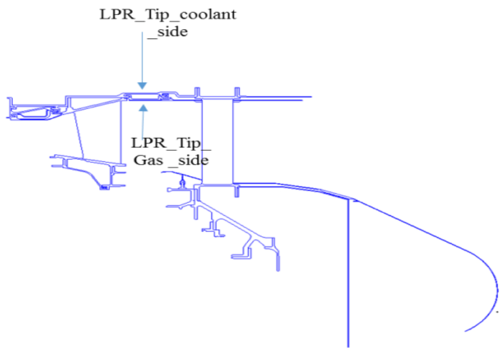

Figure 16: Locations considered on turbine casing and exhaust strut

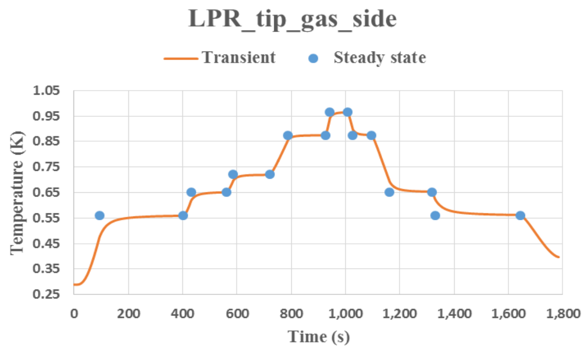

Figure 17 (a): Comparison between steady and transient temperature of turbine casing and exhaust strut on gas side

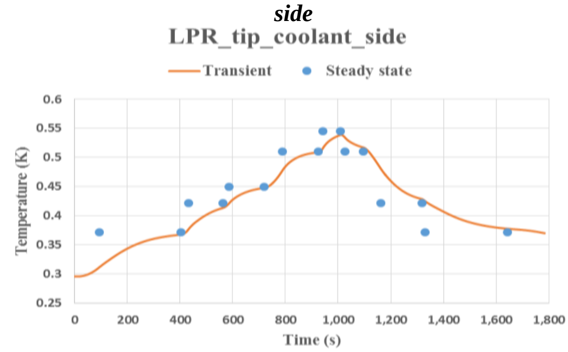

Figure 17 (b): Comparison between steady and transient temperature of turbine casing and exhaust strut on coolant side

D. Parametric analysis:

Parametric analysis carried out for static structures of aero engine. Analysis carried out by varying aerodynamic parameters such as heat transfer coefficient on hot gas side and coolant side, hot gas temperature and coolant temperature by ±20% and corresponding hot gas side metal temperature is estimated. It is observed that change in metal temperature of about ±105K for variation of gas temperature of ±20%. Hence it can be concluded that among all the parameters hot gas temperature is the critical parameter affecting metal temperature.

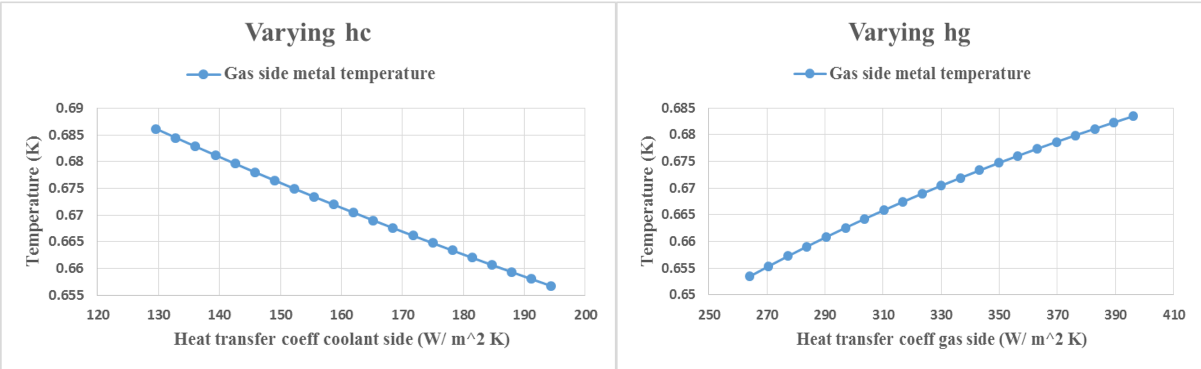

Figure 18: Metal temperature for variation of heat transfer coefficient on coolant side and hot gas side (2EM location)

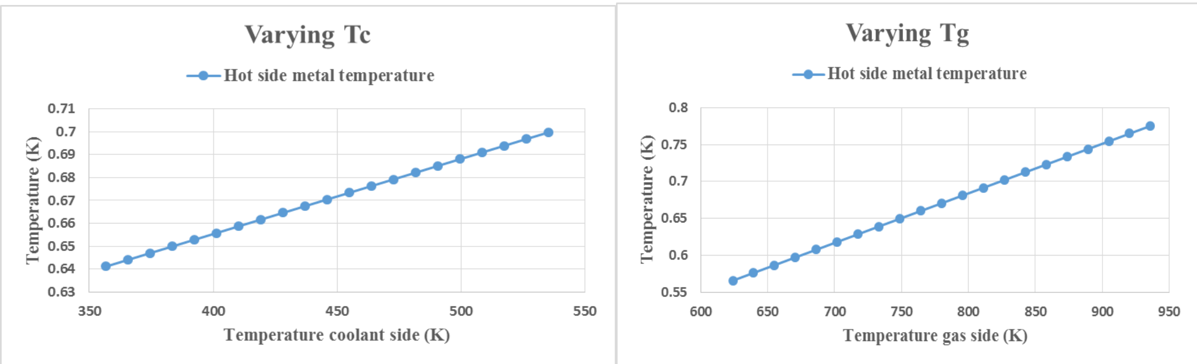

Figure 19: Metal temperature for variation of gas temperature on coolant side and hot gas side (2EM location)

Table 5: Parametric analysis at 2EM location

Variable (2EM)	Value	Effect in T_{metal}, K
Coolant temperature	±20%	±29K
Gas temperature	±20%	±105K
Coolant Heat transfer Coefficient	±20%	±15K
Gas Heat transfer Coefficient	±20%	±16K

It is observed from above figure that increasing heat transfer coefficient on gas side, hot gas temperature and coolant temperature increases metal temperature whereas increasing heat transfer coefficient on coolant side decreases metal temperature.

IV. CONCLUSIONS

Thermal analysis of static structures of aero engine is carried out. Heat loads coming on to the casings is estimated using correlations for different zones to carry out finite element analysis. The following conclusions were drawn from the following analysis carried out.

1. Steady state thermal analysis carried out for different steady state conditions and it is observed that maximum nodal temperature is occurring near to the high pressure turbine nozzle guide vane region and the temperature is around 1165K.
2. The casing temperatures are measured during engine test with the help of thermocouples and temperature prediction carried out for steady state and transient temperature at few locations and steady state temperatures are within 5% of measured temperatures. The

measured transient response is matching with the estimated transient trend.

3. By comparison of steady state temperatures and transient temperatures, it is observed that thermal response at rotor section will be faster than stator section.
4. Steady state temperatures at rotor section is more than transient temperature, which leads to estimation of higher thermal growth leading to maintain higher cold clearances during assembly. This will deteriorate the performance of engine due to higher tip clearances.
5. From parametric analysis concluded that metal temperature is more sensitive to gas temperature.

ACKNOWLEDGMENT

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FUTURE WORK

Static structures consist of components which are discrete and also components of Axi-symmetry in nature. Hence it is necessary to carry out 3D analysis of static structures to capture real growths, but 3D analysis requires high end computers as well as it requires more time.

REFERENCES

[1] Harish Agarwal and Srikanth Akkaram, " Reduced Order Clearance Models For Gas Turbine Applications" 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference 7-10 April 2008, Schaumburg, IL

[2] Alexander N. Arkhipov, Vladimir V. Karaban, Igor V. Putchkov "The Whole Engine Model For Clearance Evaluation" Proceedings of ASME Turbo Expo 2009.

[3] Power for Land, Sea and Air GT2009 June 8-12,2009, Orlando, Florida, USA

[4] P. Pilidis and N. R. L. Maccallum "The Effect of Heat Transfer on Gas Turbine Transients" International Gas Turbine Conference and Exhibit, Dusseldorf, West Germany – June 8-12,1986

[5] D. K. Hennecke and K. Trappmann "Turbine Tip Clearance Control in Gas Turbines" MTU Motoren and Turbinen – Union Munchen GmbH Postfach 500640 Munich, Germany

[6] B. Glezer "Turbine Blade Tip Clearance Improvement" International Gas Turbine and Aero engine Congress and Exposition, Orlando, FL June 3-6, 1991

[7] Scott B. Lattime and Bruce M. Steinetz " Turbine Engine Clearance Control Systems: Current Practices and Future Decisions" 38th Joint Propulsion Conference and Exhibit cosponsored by AIAA,ASME,SAE, and ASEE Indianapolis, Indiana, July 7-10, 2002

[8] "General Requirements for Measurement of Engine and Component Transients" AGARD-AD.320

[9] P. Pilidis and N. R. L. Maccalum "A Study of The Prediction of Tip and Seal Clearances and their Effects in Gas Turbine Transients" The American Society of Mechanical Engineers St., New York, N.Y. 10017

[10] P F Neal "Mechanical and Thermal Effects on the Transient and Steady State Component Performance of Gas Turbines" Technical Design group, Rolls Royce Limited.

[11] Ansys theory guide, www.ansys.com ANSYS, Inc. Southpointe, Canonsburg, PA.15537

[12] Klause Hunecke "Jet Engines – Fundamentals of Theory, Design and Operation" Erdogan Madenci and Ibrahim Guven "The Finite Element Method and Applications in Engineering using Ansys"