RESEARCH ARTICLE OPEN

Probabilistic Assessment of Thermal Gradient In Bolted Flange of A Gas Turbine Engine

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ABSTRACT
Recent developments of higher temperature, pressure and speed in gas turbine technology demands closure bolted flanges. Thermal analysis of bolted flange joint is also critical along with structural analysis as they experience huge thermal gradients. Stresses induced due to thermal gradients also influence the Low cycle fatigue (LCF) life of the flange joint especially during transient conditions of the flight cycle. Several parameters like flange dimensions, gap between the flanges and thermal boundary conditions on the inner and outer sides of joint influence flange joint thermal gradient.

The present study investigates the variation of flange gradient the variation flange height, flange thickness and gap. Both parametric and probabilistic studies have been carried out to identify most significant parameter which influences the flange gradient. In probabilistic approach the variation in the input parameters can be captured using probabilistic sampling like normal distribution, which is closer to the reality. The results presented in this paper will be helpful to the designer in designing better bolted flange joints with improved LCF life.

Keywords: Bolted flange thermal gradient, Flange height, Flange thickness, Gap, Probabilistic study on flan

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I. INTRODUCTION

Bolted flange joints perform a very important role in the closure of flanges of a gas turbine engine. They have two important functions, namely: (a). to maintain the structural integrity of the joint itself, and (b). to prevent the leakage through the flange. Thermal analysis of the flange joints is critical as they experience huge thermal gradients during the engine operation. Stresses induced because of thermal gradients also play an important role in deciding the LCF life of a flange joint. Hence accurate thermal modelling helps in predicting exact life of a flange joint. Abdel-Hakim Bouzid and Akli Nechache [1] outlined the theoretical analysis used for the determination of the steady state operating temperature and deflections in bolted flange joints. They detailed the theoretical equations necessary to predict the temperature profiles and thermal expansion difference between the joint components necessary for the evaluation of the load redistribution for the two cases of a flange pair and a flange with a cover plate. Toshimichi Fukuoka [2] proposed a simple equation for evaluating the amount of heat flow through a small gap by defining apparent thermal contact coefficient. Accordingly, a numerical approach, which could accurately analyze the thermal and mechanical behaviors of a bolted joint, was established. His study showed that only a slight difference in coefficients of linear expansion among the joint members significantly affects the variations of bolt preloads. Fumio Ando et al [3] investigated the leakage behavior of bolted flange connections using the latest computational fluid dynamics (CFD) techniques and the techniques of structural thermal analysis with nonlinear material properties in flange and gasket. The consequent start-up, normal operation and emergency shut-down conditions were considered. Thus, the leakage phenomena could be evaluated, and a guideline was proposed for maintenance. Mohd. Yousuf et al. [4] performed a parametric study on bolted flange. They have varied the flange height, thickness & gap between flanges. It has been reported that the maximum temperature gradient of flange decreases with increase in flange thickness while it increases with increase in flange height. Moreover, they have identified that the time at which maximum transient gradient occurs is independent of flange thickness as well as height.

In the present study, the process of carrying out thermal analysis on bolted flange joint has been automated using a software called Isight. The finite element model in this analysis is same as used by Mohd. Yousuf et al. [4]. Probabilistic analysis of flange joint thermal gradient is carried out with the parameters, flange height, flange thickness and gap between flanges. In probabilistic approach the variation in the input parameters can be captured using probabilistic sampling like normal distribution, which is closer to the reality

II. MODELLING APPROACH

A three dimensional finite element submodel is created using ANSYS 12.1 as shown in Fig 1. Five bolts are considered for the analysis. SOLID70 elements are used for meshing (total of 75319 elements). Thermal contact at the flange interface with bolt/nut and between the flanges is modelled with TARGE170 and CONTA174 elements. FLUID116 elements are used for fluid network to simulate the leakage through flange, bolts and nuts. Convective boundary conditions are applied using SURF152 elements. Materials made up of Nickel alloy, which can withstand temperatures up to 1200^{o}F, are chosen for the flanges and fasteners.

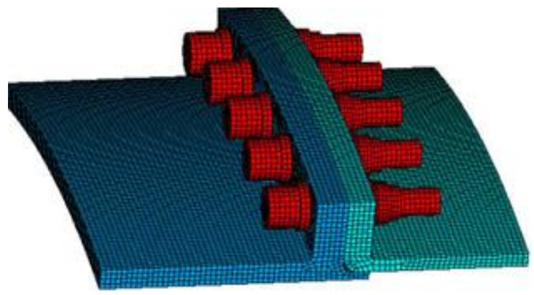


Figure 1: *Bolted flange finite element model*

The flange leakages modelled at ID snap, at gaps between flanges and bolt head/nut are similar to leakage modelling done by Mohd. Yousuf et al. [4]. The correlations used to find the convective heat transfer coefficient on the surfaces are summarized in Table. 1.

Table 1: Summary of heat transfer coefficient correlations

S. No	Zone name	Correlation Used
1	ID side	$Nu = 0.0296\ Re^{0.8}\ Pr^{0.333}$
2	Between Flanges	$Nu = 0.023\ ReD^{0.8}\ Pr^{0.3}$
3	OD side	$Nu = 0.15\ Ra^{0.33}$

1. Flight Cycle Mission

The sample mission started with stabilized idle condition and accelerated to takeoff in 15 secs. To stabilize the temperatures at takeoff, a dwell of 25 minutes was introduced, then the engine was decelerated to idle condition in 25 secs and then engine was allowed to run for a period of 40 minutes at idle condition. The mission cycle is illustrated in Fig 2.

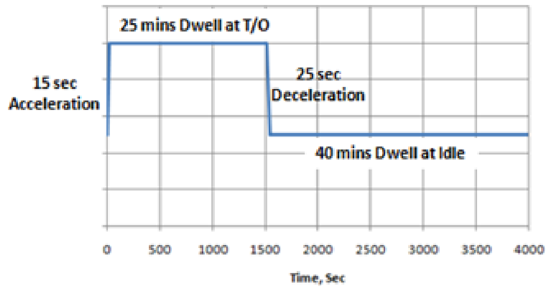


Figure 2: *Flight Cycle mission*

2. Process Automation

Figure 3 represents the flow automation loop used for the analysis of bolted flange gradient. A parametric study available in the DOE component is used for varying flange height, thickness & gap between flanges. The minimum, maximum, baseline values and number of levels of parameters are given as input in the DOE. The DOE component runs for number of levels provided and for the all variables. While varying a parameter, all other parameters are kept at their baseline values. The range of parameters used in the analysis are presented in Table.2.

Figure 3: *Process automation loop*

The components, Gap_upd_idle and Gap_upd_TO available in the loop are used to update the gap values in the flow model files at idle and TO, respectively. The next two components are used to calculate the flows using updated gap model files. The output of these flow values are red using flow_idle and flow_TO components. The components, Height_var and Thick_var are used to update the height and thickness values of FE model. The component, calculate_HTC is used to calculate the heat transfer coefficient using updated gap and flow values. Then ansys transient run is performed in the ANSYS_run component. It gives the temperature values of top and bottom location of both left and right flanges for all the times points. Then SS idle gradient, SS TO gradient, and maximum transient gradient and time at which maximum gradient occurs are calculated using a MATLAB component, named in the loop as Post processing. The output of MATLAB component specified above are red using read outputs component. This whole process repeats for all the levels of parameters. Finally, regression analysis is carried out for the output parameters for the variation of input.

Table 2: Parameters and their ranges used for the Parametric study

Range of Parameter					
Parameter	Unit	Baseline value	Minimum value	Maximum value	No. of levels
Gap	mil	0.7	0.4	1	50
Height	% Change	0	0	12.5	50
Thickness	% change	0	0	50	50

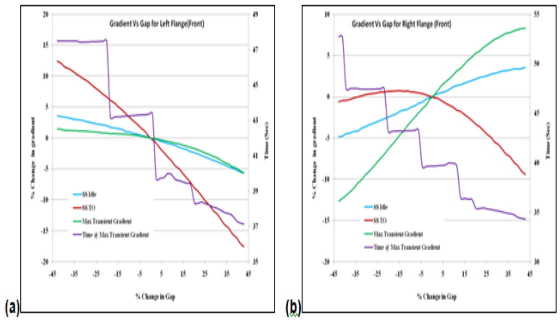
For the probabilistic study, Monte Carlo component is used instead of DOE. Monte Carlo is a class of computational algorithm used for random sampling. For each parameter, mean and standard deviation are specified. For the specified number of simulations, inputs are generated randomly from the normal distribution curve, then deterministic study is performed over the inputs. The parameters and their ranges used for the probabilistic study is represented in Table.3.

Table 3: Parameters and their ranges used in the probabilistic study

Range of Parameter						
Param eter	Unit	Mean value	Standard deviation	Min. value (mean - 3σ)	Max. value (mean + 3σ)	No. of simul ations
Gap	mil	0.7	0.2	0.1	1.3	200
Height	% Change	6	2	0	12	
Thickn ess	% change	30	10	0	60	

III. RESULTS AND DISCUSSION

Figures 4(a) and 4(b) represent the variation of percentage change in gradient with percentage change in gap for left and right flanges, respectively. The percentage change is calculated from the baseline value of input parameters and corresponding output parameters. It is observed that both SS idle and maximum transient thermal gradient



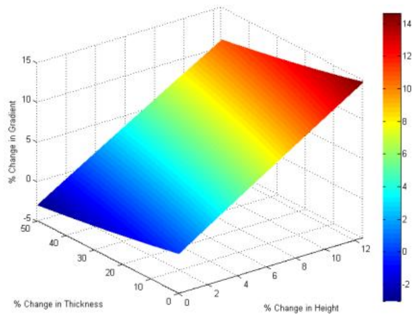
Variation of % change in temperature gradient of (a) Left flange (b) Right flange with % change gap for different flight points

behaviour of left and right flanges are different in nature. When the left flange gradient decreases with increases with gap, the right flange shows increase in trend for the increase in gap. If we consider the left flange, the bottom surface of it exposes to the hotter environment with higher heat transfer coefficient and top surface is exposes to the lower heat transfer coefficient and temperature. With increase in gap, an additional heat up is added to the flange, moreover, this enhance the heat transfer from bottom to top of the flange which results in decrease in flange gradient. When the right flange is considered, as it has snap joint with left flange, the bottom portion of the flange is not directly exposing to the hotter environment. So, the gradient is driven mainly by the leakage through flange and the maximum transient gradient increases with increase in gap is seen in Fig. 4(b).

It is seen in Fig. 4(a) and (b) that the time at which maximum transient occurs in not smooth with percentage change in gap. This is due to automatic time step of ANSYS. It is observed that after completion of 47 sec run, it jumps to 43 sec both for -25% and -20% change in gap. Due to which even for a very small change in transient gradient, the respective time shift as significant from 47 sec to 43 sec.

The percentage change in gradient with height and thickness at SS TO condition is represented in Figs. 5(a) and (b) for left and right flanges, respectively. It is observed Fig. 5(a) that the flange temperature gradient increases with increase in flange height due to increase in conduction resistance between ID and OD and it decreases with increase in flange thickness due to increase in conduction area which leads to more heat transfer from ID to OD flange. Similar behaviour is observed in right flange also, however, the gradient varies non linear with increase in flange thickness.

The percentage change in maximum gradient with height and thickness at accel is represented in Figs. 6(a) and (b) for left and right flanges, respectively. It is observed that both left and right flanges show similar behaviour like SS TO condition. However, the magnitude of gradient is lower in accel when compared to SS TO condition.



(a) **(b)**

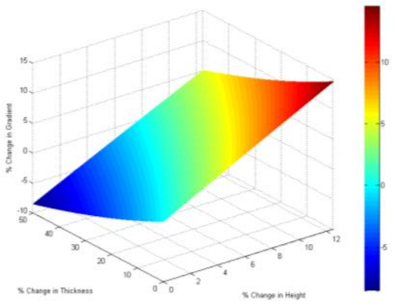
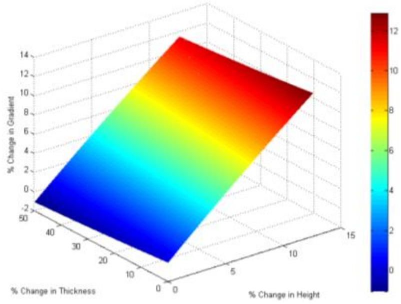
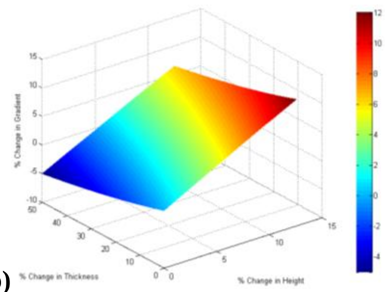


Figure 4: *Variation of % change in temperature gradient of (a) Left flange (b) Right flange with % change height and thickness at SS TO*



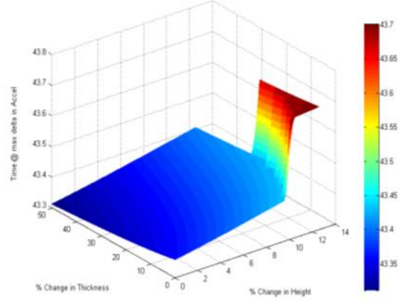
(a)



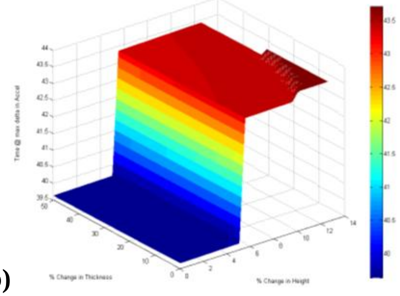
(b)

Figure 5: *Variation of % change in maximum temperature gradient at accel for (a) Left flange (b) Right flange*

The time at which maximum transient gradient occur is represented in Figs. 7(a) and (b) for left and right flanges, respectively. It is seen that the time at which maximum gradient occur in accel is independent of change in flange thickness and it occur at higher value of time for the increase of flange of flange height. The reason why sudden changes in time occurs is already explained above.



(a)

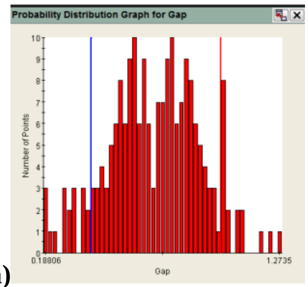


(b)

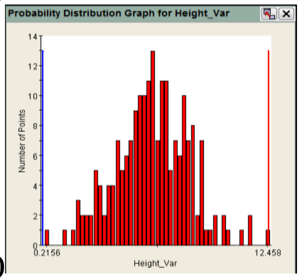
Figure 6: *Variation of time at maximum temperature gradient at accel for (a) Left flange (b) Right flange*

Figure 8 represents the probabilistic variation of inputs. The mean and standard deviation applied for in the input variables are represented in Table. 2. The probabilistic analysis is carried out to understand whether any significant changes of output variables, flange gradient & time. The number of times a particular input variables chosen for carrying out deterministic study is seen in Fig. 8. As Monte Carlo algorithm uses normal distribution curve to select input variables, it is seen that almost 68% of samples falls in σ range.

Figures 9(a) and (b) show that left flange probabilistic variation of maximum gradient at accel and time at which maximum gradient occur, respectively. It is seen that the percentage change of maximum gradient at accel occur is about ±11% from the mean (0%) and the time at which the maximum gradient at accel occur is between 33.2-59.2 sec. However, the gradient falls frequently between 4 to 6% from the mean value and it is observed that the time at which maximum gradient falls frequently at 47.74 sec.



(a)



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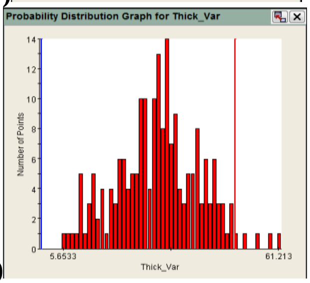
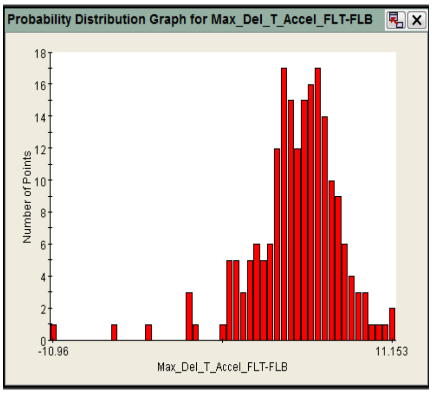


(c)

Figure 7: *Generated probabilistic variation of inputs for (a) gap (b) height (c) thickness*



(a)

(b)

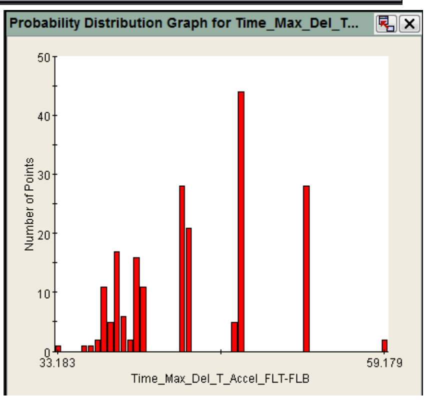
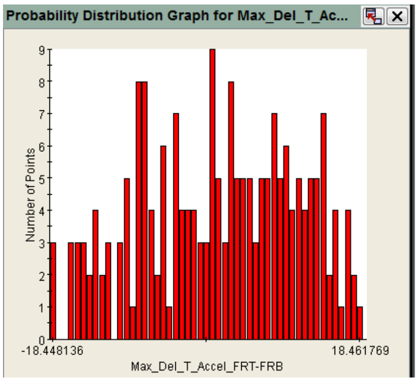


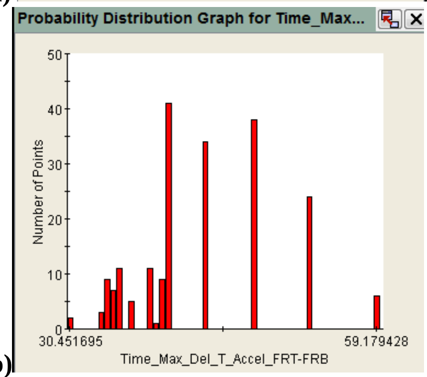
Figure 8: *probabilistic variation of (a) maximum gradient at accel (b) time at maximum gradient at accel for left flange*

Figures 10(a) and (b) show that right flange probabilistic variation of maximum gradient at accel and time at which maximum gradient occur, respectively. It is seen that the percentage change of maximum gradient at accel occur is about ±18% from the mean (0%) and the time at which the maximum gradient at accel occur is between 30.5-59.2 sec. However, the gradient falls frequently on 0.75% from the mean value and it is observed that the time at which maximum gradient falls frequently at 39.6 sec.

The minimum time at which transient gradient occur and respective input parameters are presented in Table. 4. It shows that right flange attains maximum gradient within shorter period of time.



(a)



(b)

Figure 9: *probabilistic variation of (a) maximum gradient at accel (b) time at maximum gradient at accel for right flange*

Table 4: Transient gradient at minimum accel time and respective parameters

Transient Gradient @ Minimum accel time					
	Min. Time (Sec)	Transient Gradient (%)	Gap (%)	Height (%)	Thickness(%)
Left flange	33.18	-10.96	1.23	1.92	42.24
Right Flange	30.45	15.02	1.27	6.75	33.43

IV. CONCLUSIONS

1. Parametric and probabilistic studies have been carried out to investigate the flange gradient for the variation of parameters, the flange height, flange thickness and gap.

2. It is observed that both SS idle and maximum transient thermal gradient behaviour **o**f left and right flanges are different in nature.

3. The flange temperature gradient increases with increase in flange height due to increase in conduction resistance between ID and OD

4. The flange temperature gradient decreases with increase in flange thickness due to increase in conduction area which leads to more heat transfer from ID to OD flange.

5. The magnitude of gradient is lower in accel when compared to SS TO condition.

6. It is seen that the time at which maximum gradient occur in accel is independent of change in flange thickness and it occur at higher value of time for the increase of flange of flange height.

7. In the left flange, the gradient falls frequently between 4 to 6% from the mean value and it is observed that the time at which maximum gradient falls frequently at 47.74 sec.

8. In the right flange, the gradient falls frequently on 0.75% from the mean value and it is observed that the time at which maximum gradient falls frequently at 39.6 sec.

9. For the considered parameters and its standard deviation values, the minimum time at which transient gradient occur at left and right flanges are 33.18 sec and 30.45 sec, respectively.

NOMENCLATURE

Accel: Acceleration
Decel: Deceleration
ID: Inner Diameter
LCF: Low Cycle Fatigue
MAX: Maximum
min: Minutes
Nu: Nusselt Number
OD: Outer Diameter
Pr: Prandtl Number
Ra: Rayleigh Number
Re: Reynolds Number
sec: Seconds
SS: Steady State

Subscripts

D: Diameter

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