High Cycle Fatigue Estimation of Aircraft Exhaust T50 Thermocouple
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Abstract— A limiting factor in a gas turbine engine is the temperature of the turbine section. The temperature of a turbine section must be monitored closely to prevent overheating the turbine blades and other exhaust section components. One common way of monitoring the temperature of a turbine section is with an EGT gauge. EGT is an engine operating limit used to monitor overall engine operating conditions.

Key words: Aerospace, FEM, Fatigue Strength, Nonlinear Static Analysis

I. INTRODUCTION
Engineering machines and structure in service, experiences vibration, and their design generally requires consideration of their dynamic behaviour. The type of input forces experienced by different components of aerospace in service is dynamic. The progressive, localized and permanent structure change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than the tensile strength of the material which may culminates in cracks and causes fracture after a sufficient number of fluctuations is known as fatigue. Fatigue and durability design of any component of an aerospace structure plays an important role to ensure reliability. The total damage and life of a structure is due to a combination of static and dynamic loads arising from engine vibrations, service load. The basic aim is to enable fatigue life calculations to be done at the design stage of a development process. It is necessary to clarify the term fatigue as the estimation of fatigue life when the stress or strain histories obtained from the structure or component.

A. Exhaust Gas Temperature Thermocouple (EGT)
A limiting factor in a gas turbine engine is the temperature of the turbine section.

Fig. 1: Overview of Aircraft Exhaust System
The temperature of a turbine section must be monitored closely to prevent overheating the turbine blades and other exhaust section components. One common way of monitoring the temperature of a turbine section is with an EGT gauge. EGT is an engine operating limit used to monitor overall engine operating conditions.

II. OBJECTIVE
– Strength assessment using static non-linear analysis.
– Design assessment for shock requirement.
– High cycle fatigue life estimation.

III. SCOPE OF WORK
The Main focus of this Project work is to Estimation of HCF for aircraft exhaust T50 thermocouple. Finite element model has been created very appropriate elements in Ansys workbench. The stress response output from Vibration analysis is used for fatigue life estimation.

IV. MATERIAL SELECTION
A. Support Tube Material:
Support tube and simplex element has been modeled with Inconnel 625 and its mechanical properties are listed below.

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Young’s Modulus(E)</td>
<td>1.478*10^5 N/mm²</td>
</tr>
<tr>
<td>2</td>
<td>Poisson’s Ratio(θ)</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Density(ρ)</td>
<td>8.44*10^-6 Kg/mm³</td>
</tr>
<tr>
<td>4</td>
<td>Yield Strength(σy)</td>
<td>262 N/mm²</td>
</tr>
<tr>
<td>5</td>
<td>Ultimate Strength(σu)</td>
<td>675.6 N/mm²</td>
</tr>
<tr>
<td>6</td>
<td>Endurance Strength(σe)</td>
<td>234.4 N/mm²</td>
</tr>
</tbody>
</table>

Table 1: Mechanical properties of Inconnel 625 material.

B. Lid Materials:
Lid housing and terminal has been modeled with AISI304 steel and its mechanical properties are listed below.

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Young’s Modulus(E)</td>
<td>1.79*10^5 N/mm²</td>
</tr>
<tr>
<td>2</td>
<td>Poisson’s Ratio(θ)</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>Density(ρ)</td>
<td>7.75*10^-6 Kg/mm³</td>
</tr>
<tr>
<td>4</td>
<td>Yield Strength(σy)</td>
<td>99.7 N/mm²</td>
</tr>
<tr>
<td>5</td>
<td>Ultimate Strength(σu)</td>
<td>310.2 N/mm²</td>
</tr>
<tr>
<td>6</td>
<td>Endurance Strength(σe)</td>
<td>110.3 N/mm²</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of AISI304 steel

C. Bolts Material:
Bolt has been modeled with Inco718 and its mechanical properties are listed below.

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Young’s Modulus(E)</td>
<td>1.89*10^5 N/mm²</td>
</tr>
<tr>
<td>2</td>
<td>Poisson’s Ratio(θ)</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Density(ρ)</td>
<td>7.47*10^-6 Kg/mm³</td>
</tr>
<tr>
<td>4</td>
<td>Yield Strength(σy)</td>
<td>896.3 N/mm²</td>
</tr>
<tr>
<td>5</td>
<td>Ultimate Strength(σu)</td>
<td>1089.3 N/mm²</td>
</tr>
</tbody>
</table>

Table 3: Mechanical properties of Inco718 steel
<table>
<thead>
<tr>
<th>6</th>
<th>Endurance Strength (σe)</th>
<th>448.1N/mm²</th>
</tr>
</thead>
</table>

Table 3: Mechanical properties of Inco 718 used in Bolts.

V. CATIA V-5 MODEL

![Fig. 2: Representation of T50 thermocouple in 3D view.](image)

VI. FINITE ELEMENTS MODEL

![Fig. 3: Finite element model of T50 thermocouple](image)

VII. STATIC STRESS ANALYSIS

A. Boundary Condition

![Fig. 4: T50 thermocouple Boundary condition details](image)

Static analysis is carried out 600°c for bolt strength estimation. Bolt pretension of 8629.5 N applied to T50 thermocouple in Z direction with respect to local coordinate system.

![Fig. 5: Bolt pretension is applied to T50 thermocouple.](image)

B. Results and Discussion

1) Total Displacement Plot

![Fig. 6: Total displacement plot of T50 thermocouple.](image)

Due to bolt preload total displacement is 0.0045 mm and it occurs at bolt location.

2) Max Bolt Stress

![Fig. 7: Stress (Von-Misses) of Bolt in T50 thermocouple](image)
High Cycle Fatigue Estimation of Aircraft Exhaust T50 Thermocouple

Estimation of Aircraft Exhaust T50 Thermocouple

Max bolt normal stress of 248.4 MPa is less than the material allowable strength of 552 MPa.

C. Bolt strength validation

Bolt normal stress, \( \sigma_z = \frac{P}{A} \),

Where,

\( P = \) bolt preload in N = 8629.5 N,

\( A = \) bolt cross section area in mm\(^2\) = \( \pi d^2 / 4 \)

Where, \( d = \) bolt dia= 6.35 mm

Bolt cross section area, \( A = 31.669 \) mm\(^2\)

\( \sigma_z = \frac{8629.5}{31.669} \)

\( \sigma_z = 272 \) MPa

Takeaway: Estimated bolt stress of 272 MPa is more than the analysis predicted value of 248.4 MPa and the % difference is less than 10%.

VIII. Vibration Analysis of T50 Thermocouple

A. Modal Analysis

The modal analysis has been performed for a frequency range of 0-2000 Hz and at 600°C.

1) Boundary Conditions

Fig. 9 Boundary conditions applied to T50 thermocouple.

2) Results & Discussion:

Total 2 modes are observed in the frequency range of 0-2000 Hz.

<table>
<thead>
<tr>
<th>Mode no</th>
<th>Frequency (Hz)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1168.3</td>
<td>Bending mode in X-direction</td>
</tr>
<tr>
<td>2</td>
<td>1605.5</td>
<td>Bending Mode in Y-direction</td>
</tr>
</tbody>
</table>

Table 4 Modal frequencies of T50 thermocouple

3) Mode shapes

Mode-1: Element bending mode in X-direction at 1168.3 Hz

Mode-2: Element bending load in Y-direction at 1605.5 Hz

B. Harmonic Response:

In this project harmonic analysis was carryout for the frequency range of 0-2000 Hz and overall damping ratio of 2% is considered and in the harmonic analysis an acceleration load of 9814.36 mm/s\(^2\) is applied in Y-direction.
direction. However, based on input response curve for above frequency range, analysis results are scaled by 18 factors.

Graph 6.1 response curves for scaling factor
Based on input curve actual G at 1605.5 Hz is 18 G hence the scaling factor of 18 will be used in order to get the actual response and stress results.

Fig. 11: Acceleration load applied to T50 thermocouple assembly.

1) Results and Discussion – Harmonic Analysis Frequency Response

Fig. 12: Acceleration response locations- Element

Fig. 13: Graph 9.2 Acceleration response plot

<table>
<thead>
<tr>
<th>Acceleration (mm/s²)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Response for 1G</td>
<td>2.76E+05</td>
</tr>
<tr>
<td>Output Response for 18G</td>
<td>4.97E+06</td>
</tr>
<tr>
<td>Amplification Factor (Output/Input)</td>
<td>276.380 / 9.807 = 28.15</td>
</tr>
</tbody>
</table>

2) Max Stress Plot – Element:

Graph 9.4 Frequency response plots- Element

Fig. 14: Frequency response locations- Element

Fig. 15: Equivalent (Von-Mises) Stress- Element
IX. HIGH CYCLE FATIGUE ESTIMATION

Mean stress for thermocouple is considered to be zero and alternating stresses are computed for each material considering sinusoidal sweep applied on the model in engine Y-axis.

- $\sigma_{\text{alternating}}$ - Results documented from Vibration Analysis (in Y-Direction Sinusoidal Sweep Analysis)
- $\sigma_{\text{mean}}$ - Zero Stress (Since the T50 thermocouple is not exposed to High pressure from within the engine.)

### A. Fatigue Calculation for Element:

For Inconel 625 material;
- Ultimate Strength, $\sigma_u = 675.7$ MPa @ 600 Deg C
- Endurance Strength, $\sigma_e = 234.4$ MPa @ 600 Deg C
- $\sigma_{\text{mean}} = 0$
- $\sigma_{\text{alternating}} = 9.36$ MPa (from Vibration Analysis)

Fatigue Strength Margin = (Endurance Limit/ Vibration alternating Stress) – 1
Fatigue Strength Margin = (234.4/9.36) – 1
Fatigue strength Margin = 24.04

Goodman Curve for Element:

Takeaway: Element is having infinite design life of more than 1E7 cycles

### B. Fatigue Calculation for Support Tube:

For Inconel 625 material;
- Ultimate Strength, $\sigma_u = 675.7$ MPa @ 600 Deg C
Endurance Strength,  \( \sigma_e = 234.4 \text{ MPa} @ 600 \text{ Deg C} \)
\( \sigma \) mean = 0
\( \sigma \) alternating = 3.06 MPa (from Vibration Analysis)
Fatigue Strength Margin = (Endurance Limit/ Vibration alternating Stress) – 1
Fatigue Strength Margin = \( \frac{234.4}{3.06} \) – 1
Fatigue strength Margin = 75.60

1) Goodman Diagram for Support Tube:

Graph 10.2 Goodman Curve for Support Tube

Takeaway: Support Tube is having infinite design life of more than 1E7 cycles

X. CONCLUSION

It is concluded that T50 thermocouple design provides the best balanced solution with regard to static and dynamic loads of critical condition. The numerical and analytical results of bolt analysis is 248.4 MPa and 272 MPa respectively, which is below the yield Strength limit of 552 MPa and the percentage difference in the results is less than 10% which is acceptable. By this we can conclude that Bolt can withstand the applied load.

Vibrational characteristics like natural frequency and mode shapes are obtained using modal analysis by this predict of resonance is possible. Mode-2 with natural frequency of 1605.5 Hz is considered as critical mode as it is having high effective mass in Y direction compared to X & Z direction and mass participation Ratio 1.

Steady- state response of a T50 thermocouple is achieved using Harmonic response analysis. It is analysed for the critical frequency (mode-2) in Y- direction. Graph of displacement and stress is plotted against the frequency; by this peak stress is found. The attained results are acceptable and fall under the limit.

Fatigue estimation met the design requirements of 1E7 cycles using Goodman diagram.

XI. SCOPE FOR FUTURE WORK

- Exploring other cost effective materials with minimum weight.
- Exploring other alternative manufacturing processes like additive manufacturing.
- Dynamic analysis can be carried out for the Impact loading and random changes of the load on Exhaust T 50 thermocouple system.

REFERENCES