Improving the Accuracy of Dynamic Vibration Fatigue Simulation

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1. Introduction

2. Dynamics and the frequency response function (FRF)

3. Using finite element analysis (FEA) for structural and durability predictions

4. What’s important in fatigue

5. Role of vibration in fatigue

6. Experimental modal analysis

7. Improving FEA and fatigue analysis with experimental modal analysis

8. Summary
Dynamics and the Frequency Response Function

- All structures have resonant frequencies they like to move at.
- A small amount of excitation at a resonant frequency results in a large response.
Dynamics and the Frequency Response Function

- The Frequency Response Function (FRF) describes system’s response to excitation.
- The FRF can be predicted analytically...
- ...or measured experimentally.
Damping and the Frequency Response Function

- The resonant frequency is determined by mass and stiffness.
- The magnitude of the response is heavily dependent on damping.
Dynamic Finite Element Analysis

- Finite element analysis is a proven way to predict structural response.
- Analysis can be linear, nonlinear, static, dynamic, transient, thermal, etc.
- Dynamics need to be accounted for if excitation frequencies are greater than 1/3 of the structure’s lowest resonant frequency.
What’s Important in Fatigue?

\[ S_R = C \cdot N_f^b \]

\[ Damage = \left( \frac{S_R}{C} \right)^{-\frac{1}{b}} \]

\[ Damage \propto S_R^{\sim 5-10} \]
Changes in Stress, Changes in Life

$$\frac{D_2}{D_1} = \left( \frac{S_{R2}}{S_{R1}} \right)^{-\frac{1}{b}}$$

Assume the slope of the SN curve for a given material is $b = -0.2$

- What if the stress increases by 20%?
  - $S_{R2}/S_{R1} = 1.20$
  - $D_2/D_1 = 1.2^{(1/0.2)} = 2.5$

- What if the stress doubles?
  - $S_{R2}/S_{R1} = 2.0$
  - $D_2/D_1 = 2.0^{(1/0.2)} = 32$

Damage increases by 2.5x

Damage increases by 32x
Vibration in Fatigue

• Dynamic excitation can quickly lead to a large number of stress cycles....

• Engine at idle = 100,000 combustion cycles per hour

• And the size of the stress cycle can increase significantly.

![Graph showing vibration frequency response with 2% and 5% damping]
Impulse Response and Fatigue Life

Example response to a unit impulse

2% damping

5% damping

Example SN curve used ($b=-0.1$)
Influence of Damping on Fatigue Life

- A damping coefficient is often assumed (typ. 5%) for all modes.

- A small error in damping can lead to a large error in the fatigue life estimate.

- Example: 3% versus 5% damping ratio can lead to fatigue life estimates of an order of magnitude apart.

Good fatigue life predictions rely heavily on using realistic damping ratios.
Experimental Modal Analysis

Modal characteristics and the FRF can be determined experimentally.

- Instrument the component with accelerometers.
- Excite it with either a force hammer or a shaker table.
Experimental Modal Analysis

- Measured excitation and response can be used to calculate the FRF.
- Results for each mode include:
  - Resonant frequency
  - Mode shape
  - Damping ratio

Excitation

Responses

Modal damping coefficients

Compare measured vs. regenerated FRF

Modal damping coefficients

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Calculating Damping from Experimental Data

- Damping can be calculated from the response’s decay in the time domain...

- ...or from the width of the FRF’s peak in the frequency domain.
Validate and Enhance FE Modelling

Are FE results believable?

- Compare natural frequencies and mode shapes between test and CAE

- Quantify damping
Virtual Strain Gauge and Correlation

- Use Virtual Strain Gauges to correlate physical tests with FE results
- Extracted strains can be compared graphically or using statistical metrics
Validation of the Finite Element Model

- Compare modal frequencies and mode shapes
- Calculate modal damping
- Use virtual strain gage for correlation

- Validate boundary conditions, stiffness and mass distribution
- Correctly predict the magnitude of the stress response
- Validate meshing, boundary conditions, and loading
Case Study: An Exhaust System
Comparison of Modal Responses

**MODE 1**
1st vertical bending

- **FE** 119 Hz
- **Experimental** 104 Hz

(Top view)

**MODE 2**
1st horizontal bending

- **FE** 141 Hz
- **Experimental** 150 Hz

(Top view)
Comparison of Modal Responses

**MODE 3**
Brackets bending

- FE: 244 Hz
- Experimental: 243 Hz

**MODE 4**
Internal deflection vs.
Second bending mode?

- FE: 292 Hz
- Experimental: 292 Hz

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Conclusions

1. Damping is important in predicting component stress response.

2. Fatigue life is heavily dependent on stress response.

3. Assumed damping ratios can lead to inaccurate fatigue life predictions.

4. Experimental modal analysis (EMA) can improve FE structural analysis by:
   • validating FE results by comparison of natural frequencies and mode shapes
   • calculating actual damping ratios

5. Fatigue life estimates can be improved significantly by using these validated FE models and calculated damping ratios.
Thank you!