Development of non-contact full field stress-strain measurement techniques applied to lifting machinery’s components

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Overview

- Steps of research
- Theoretical background
- Numerical and experimental analysis
- Tools development
- Industry activities
- Further activities and conclusions
Steps of research

• To get familiar with issues related to lifting machinery
  Experience in R&D team: machinery, tests and legislations, test procedures, issues

• Depth study and application of standard measurement methods
  Laboratory experience, tests on the ground

• To develop innovative methods and techniques
  Algorithms and test benches, tools and software development

• Application to lifting machinery components

• Investigate the thermoelasticity in details spending few months abroad
Theoretical background

Thermoelastic Stress Analysis

\[ \Delta T = -\frac{T_o \alpha_l}{\rho c_p} (\Delta \sigma_{ii} + \Delta \sigma_{jj}) \]

\[ \alpha_l = \text{Thermal expansion coefficient [m/K]} \]
\[ c_p = \text{Heat capacity at constant pressure [J/(Kg \cdot K)]} \]
\[ \rho = \text{Density [Kg/m}^3]\]
\[ T_o = \text{Ambient temperature [K]} \]
\[ \Delta T = \text{Temperature variation [K]} \]
\[ (\Delta \sigma_{ii} + \Delta \sigma_{jj}) = \text{Principal components of stress tensor [Pa]} \]
Theoretical background

Thermoelastic Stress Analysis

\[ \Delta T = -\frac{T_o \alpha_l}{\rho c_p} (\Delta \sigma_{ii} + \Delta \sigma_{jj}) \]
Theoretical background

Damage evaluation: time and frequency domain

Excitation
Time History

Specimen

Stress
Time History

Wöhler curve

Miner’s Rule
Cycles Counting

Dirlik

Power Spectral Density – Spectral Moments

\[ \beta_{rf_c}^{DK} = \frac{1}{2\lambda_0^{1/2}} \left[ \frac{D_1}{Q} e^{\frac{z_1^2}{2}} + \frac{D_2 Z e^{\frac{z_2^2}{2R^2}} + D_3 Z e^{\frac{z_3^2}{2}}} \right] \]

\[ \bar{D}_{rf_c}^{DK} = \frac{\nu_P}{C\lambda_0^{k/2}} \left[ D_1 Q^k \Gamma(1+k) + \sqrt{2}^k + \Gamma \left( 1 + \frac{k}{2} \right) \left( D_2 |R|^k + D_3 \right) \right] \]
Numerical and experimental analysis

Damage evaluation in frequency domain through thermoelasticity

Geometry of the sample

Modal Analysis

Measurement chain

<table>
<thead>
<tr>
<th>Structural steel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td><strong>Thermal expansion</strong></td>
</tr>
<tr>
<td><strong>Young modulus</strong></td>
</tr>
<tr>
<td><strong>Poisson</strong></td>
</tr>
<tr>
<td><strong>Shear modulus</strong></td>
</tr>
<tr>
<td><strong>Tensile strength</strong></td>
</tr>
<tr>
<td><strong>Compressive strength</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.348</td>
</tr>
<tr>
<td>2</td>
<td>198.83</td>
</tr>
<tr>
<td>3</td>
<td>271.08</td>
</tr>
<tr>
<td>4</td>
<td>445.68</td>
</tr>
<tr>
<td>5</td>
<td>796.19</td>
</tr>
<tr>
<td>6</td>
<td>1486.2</td>
</tr>
</tbody>
</table>
Numerical and experimental analysis

Damage evaluation in frequency domain through thermoelasticity

Input acceleration PSD

Strain PSD response

Thermal signal PSD response in the area where the strain gauge has been bonded

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Admission to the 3rd year  
12 September 2019
Numerical and experimental analysis

Damage evaluation in frequency domain through thermoelasticity

\[ K(\omega) = \frac{PSD_{Strain}}{PSD_{Therm}} \]

\[ \Theta(\omega) = \frac{W(\omega)}{K(\omega)} \]

Calibration function \( K(\omega) \)

Stress PSD \( \Theta(\omega) \)

Stress PSD response map

\[ \text{[Pa}^2/\text{Hz}] \]

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12 September 2019
Numerical and experimental analysis

Damage evaluation in frequency domain through thermoelasticity

**MatLab app-designer code**

```matlab
stress_psd_cut = app.data; Fmax = app.Freqmax.Value;
freq(1,:)=linspace(0,Fmax,size(stress_psd_cut,3));
PSD_exp = zeros(length(freq),size(stress_psd_cut,1)*size(stress_psd_cut,2));
k=1;
for i=1:size(stress_psd_cut,1)
    for j=1:size(stress_psd_cut,2)
        PSD_exp(:,k)=squeeze(stress_psd_cut(i,j,:));
        k=k+1;
    end
end
[~, nc]=size(PSD_exp);
for id=1:nc
    PSD = PSD_exp(:,id);
    Mom_f(1)=trapz(freq,PSD);
    Mom_f(2)=trapz(freq,PSD.*freq);
    Mom_f(3)=trapz(freq,PSD.*freq.^2);
    Mom_f(4)=trapz(freq,PSD.*freq.^3);
    Mom_f(5)=trapz(freq,PSD.*freq.^4);
    [Dcum] = dirlik2dam(Mom_f,app.a,app.b);
    D(id,1)=Dcum; end
k=1;
Imdam=zeros(size(stress_psd_cut,1),size(stress_psd_cut,2));
app.Imlife=zeros(size(stress_psd_cut,1),size(stress_psd_cut,2));
for i=1:size(stress_psd_cut,1)
    for j=1:size(stress_psd_cut,2)
        Imdam(i,j) = D(k);
        app.Imlife(i,j) = 1/D(k);
    end
end
```

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel (195,280)</td>
<td>Node 350</td>
</tr>
<tr>
<td>4.1 · 10⁻⁹ s⁻¹</td>
<td>4.8 · 10⁻⁹ s⁻¹</td>
</tr>
<tr>
<td>5.4 · 10⁻⁹ s⁻¹</td>
<td></td>
</tr>
<tr>
<td>6.9 · 10⁻⁹ s⁻¹</td>
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</tr>
</tbody>
</table>

Comparison of results
Numerical and experimental analysis

MATLAB
APP DESIGNER

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Numerical and experimental analysis

MATLAB
APP DESIGNER

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Raspberry Pi – based device for damage estimation in real-time
Industry activities

• Validation of a mathematical model that allows to predict the dynamic behavior of the engine placed on elastomeric brackets and vibration dampers

• Development of «gravity lowering system» which uses gravity force in order to allow the descent of a hybrid telehandler
Conclusions

✔ To get familiar with issues related to lifting machinery
  Experience in R&D team: machinery, tests and legislations, test procedures, issues

✔ Depth study and application of standard measurement methods
  Laboratory experience, tests on the ground

✔ To develop innovative methods and techniques
  Algorithms and test benches, tools and software development
Further activities

- **Research abroad**
  At the *Laboratory for Dynamics of Machines and Structures (LADISK)* of the Faculty of Mechanical Engineering of the University of Ljubljana

- **Application of developed method to lifting machinery components**
  Application to real cases and components of the method which allow to estimate the damage through thermoelasticity in frequency domain

- **Optimization of Raspberry Pi - based device**
  Software development and optimization; application to real cases

- **Research activities in the industry**
• Investigating additive manufactured trabecular structures: a multi-instrument approach
G. Allevi, L. Capponi, P. Castellini & al.
IEEE Transactions on Instrumentation & Measurement (2020) [in review]

• Non-stationarity and non-Gaussianity in Vibration Fatigue
J. Slavič, M. Česnik, L. Capponi, M. Palmieri, F. Cianetti, M. Boltežar
Sensors and Instrumentation, Aircraft/Aerospace, Energy Harvesting & Dynamic (2020)

• Stress and strain non-contact measurements on complex structures realized by additive manufacturing
L. Capponi; A. Quattrocchi; D. Alizzio; T. Tocci; R. Marsili; R. Montanini; G. Rossi
III National forum of Mechanical Measurement (2019)

• Collection of experimental data for multiaxial fatigue criteria verification
G. Morettini, C. Braccesi, F. Cianetti, S.M.J. Razavi, K. Solberg, L. Capponi

• The relevance of non-stationarities and non-Gaussianities in vibration fatigue
M. Česnik, J. Slavič, L. Capponi, M. Palmieri, F. Cianetti, M. Boltežar
MATEC Web of Conferences 165, 10011 (2018)

• Non-stationarity index in vibration fatigue: Theoretical and experimental research
L. Capponi, M. Česnik, J. Slavič, F. Cianetti, M. Boltežar
Thanks for your attention