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

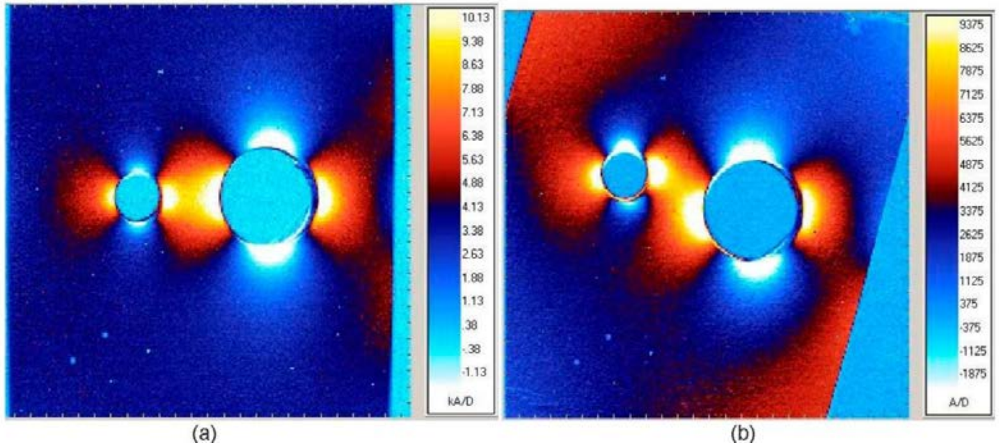
- Application to lifting machinery components

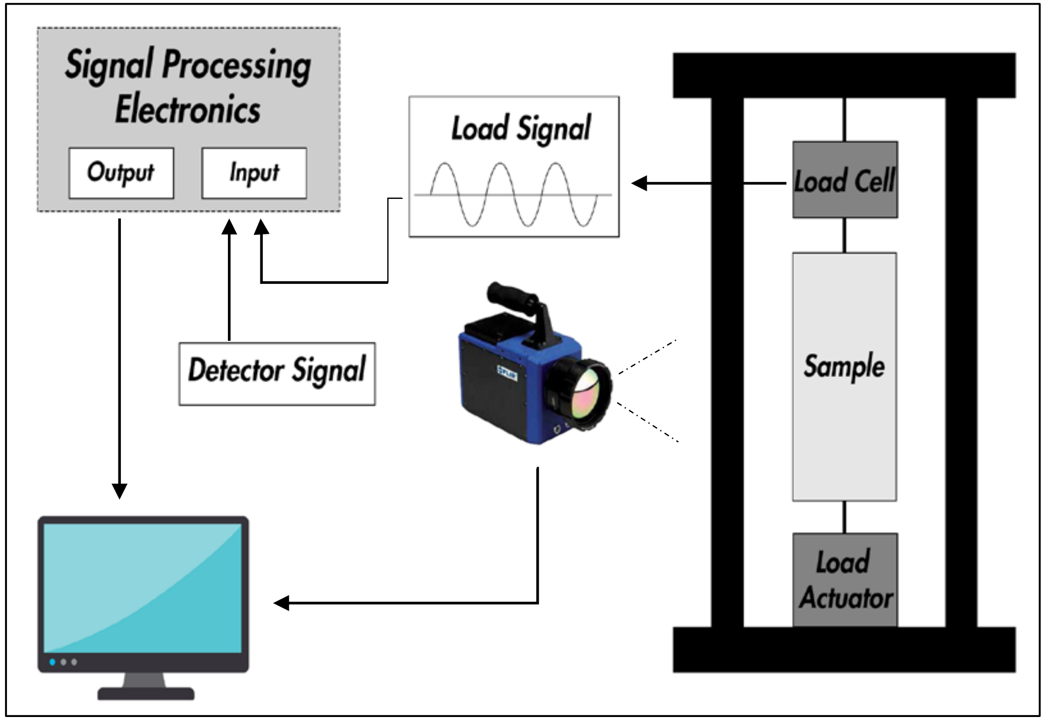
- Investigate the thermoelasticity in details spending few months abroad

Thermoelastic Stress Analysis

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

α_l = Thermal expansion coefficient [m/K]
c_p = Heat capacity at constant pressure [J/(Kg · K)]
ρ = Density [Kg/m^3]
T_o = Ambient temperature [K]
ΔT = Temperature variation [K]
$(\Delta\sigma_{ii} + \Delta\sigma_{jj})$ = Principal components of stress tensor [Pa]





TSA measurement chain

Thermoelastic Stress Analysis

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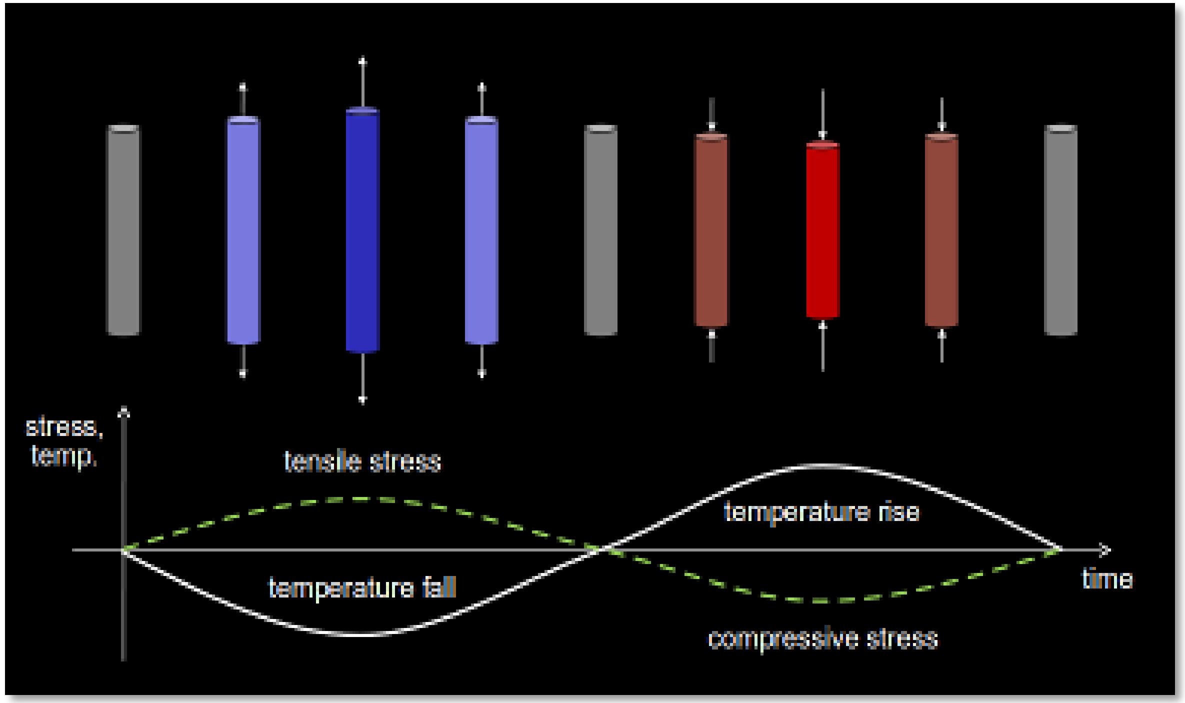
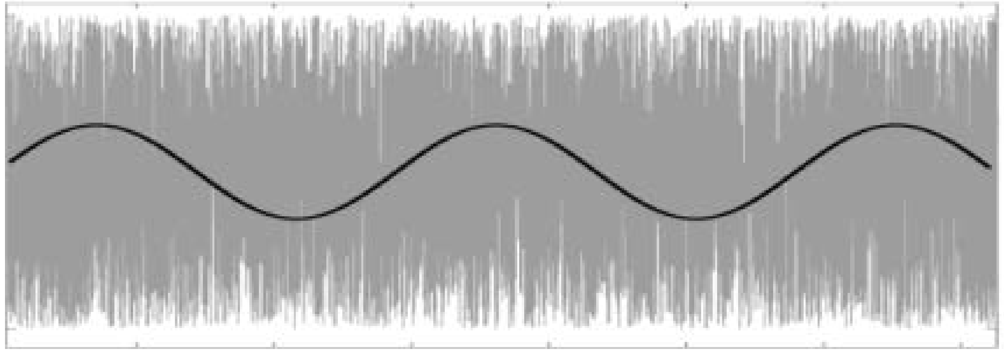
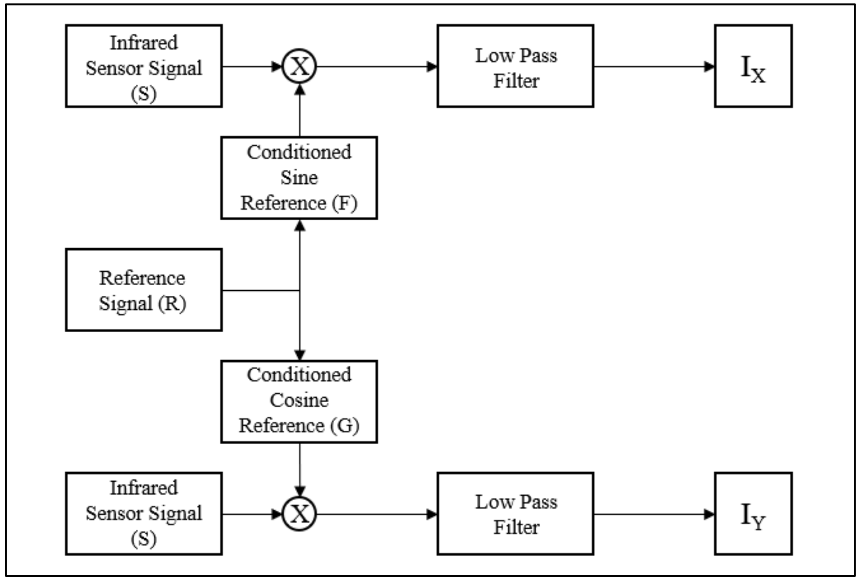


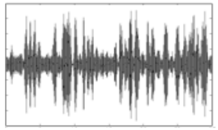




Lock-in amplifier scheme

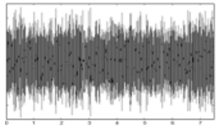
Damage evaluation: time and frequency domain

Excitation Time History

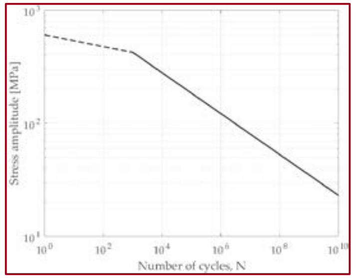


Specimen

Stress Time History

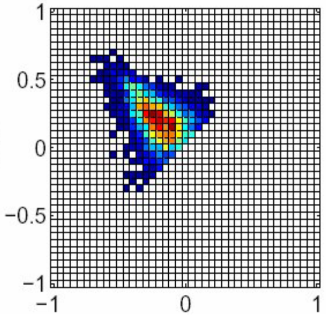


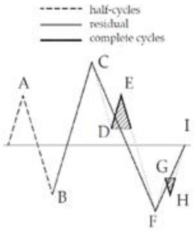
Wöhler curve



Miner's Rule

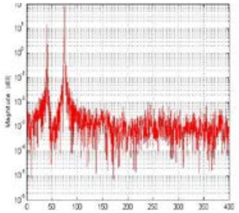
Cycles Counting





Dirlik

Power Spectral Density – Spectral Moments

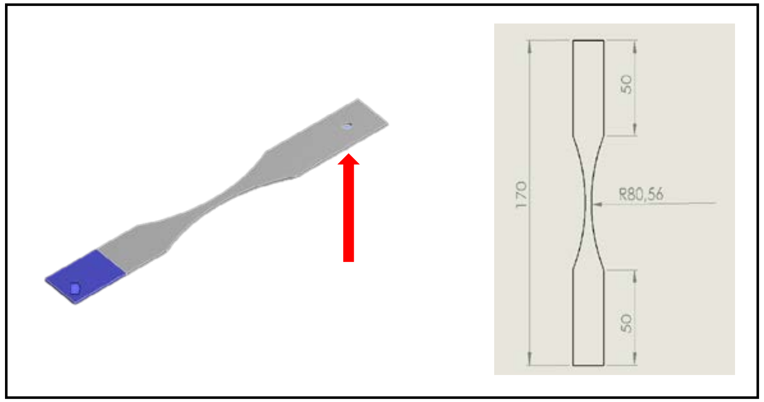


$$\rho_{rfc}^{DK} = \frac{1}{2\lambda_0^{1/2}}\left[\frac{D_1}{Q}e^{\frac{-Z}{Q}} + \frac{D_2 Z}{R^2}e^{-\frac{Z^2}{2R^2}} + D_3 Z e^{\frac{Z^2}{2}}\right]$$

$$\bar{D}_{rfc}^{DK} = \frac{\nu_p}{C}\lambda_0^{k/2}\left[D_1 Q^k \Gamma(1+k) + \sqrt{2}^k + \Gamma\left(1+\frac{k}{2}\right)\left(D_2|R|^k + D_3\right)\right]$$

Damage

Damage evaluation in frequency domain through thermoelasticity

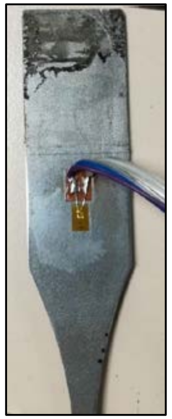


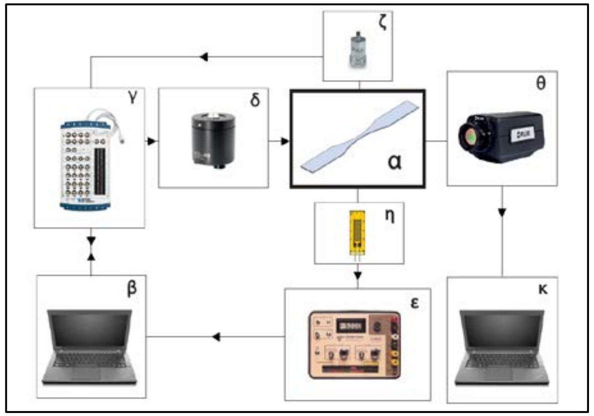
Geometry of the sample

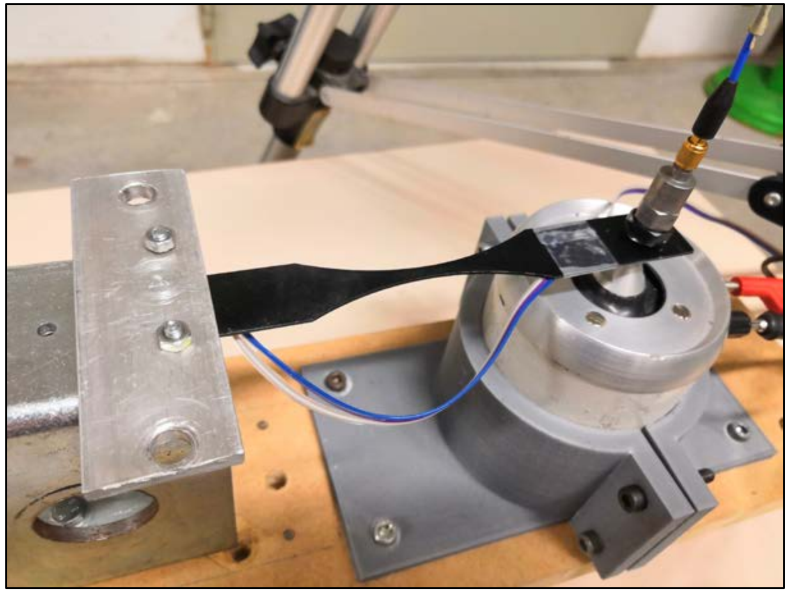
Structural steel	
Density	7850 kg/m^3
Thermal expansion	$1.2 \cdot 10^5$ °C^{-1}
Young modulus	$2 \cdot 10^{11}$ Pa
Poisson	0.3
Shear modulus	$7.69 \cdot 10^{10}$ Pa
Tensile strength	$2.5 \cdot 10^8$ Pa
Compressive strength	$2.5 \cdot 10^8$ Pa

Modal Analysis

Mode	Frequency [Hz]
1	31.348
2	198.83
3	271.08
4	445.68
5	796.19
6	1486.2

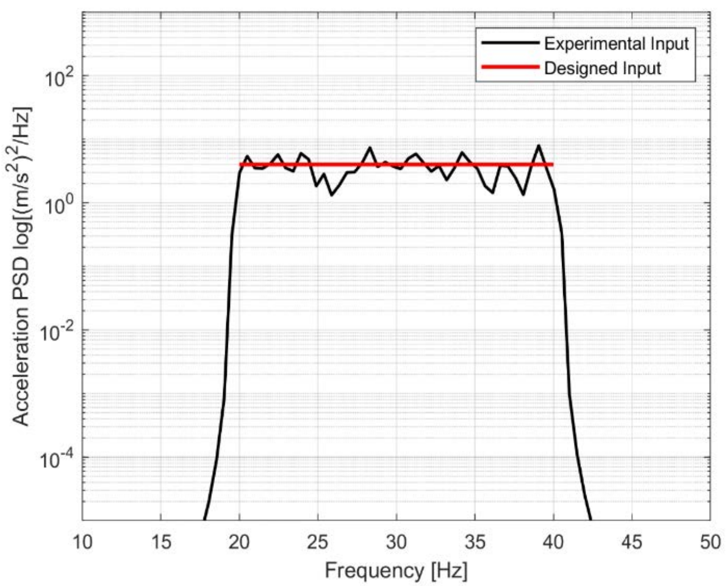




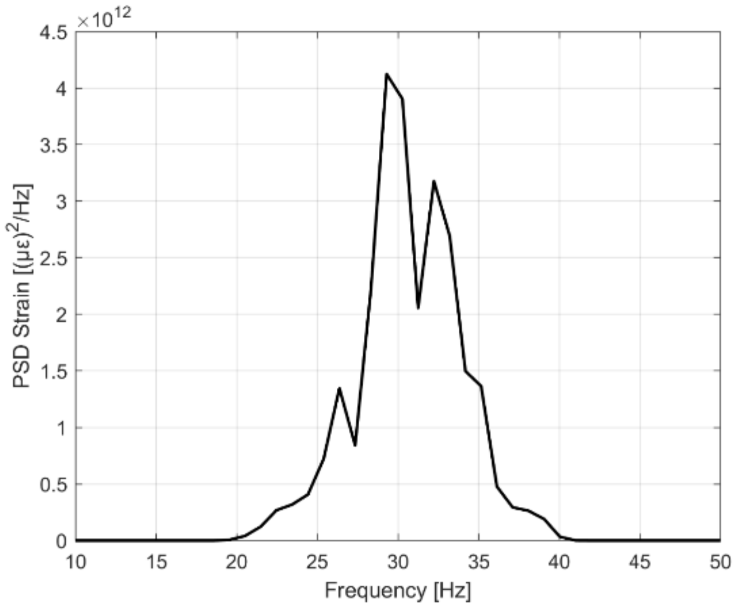


Measurement chain

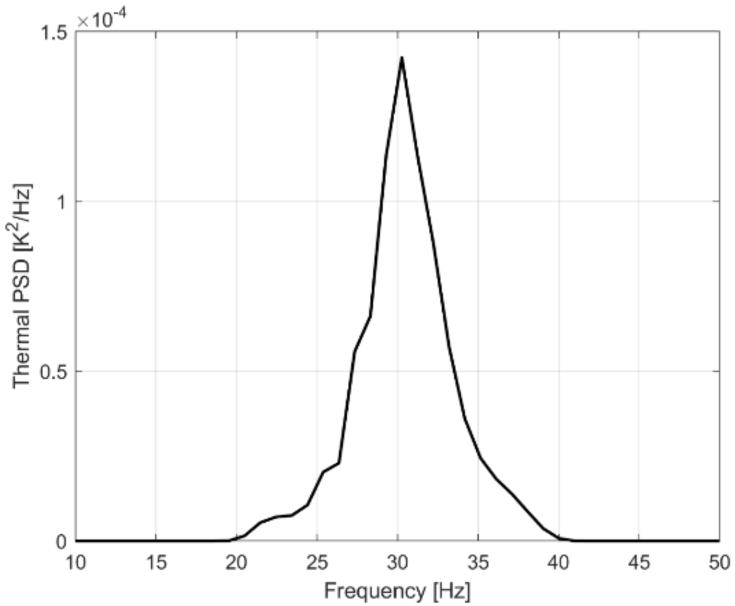
Damage evaluation in frequency domain through thermoelasticity



Input acceleration PSD



Strain PSD response

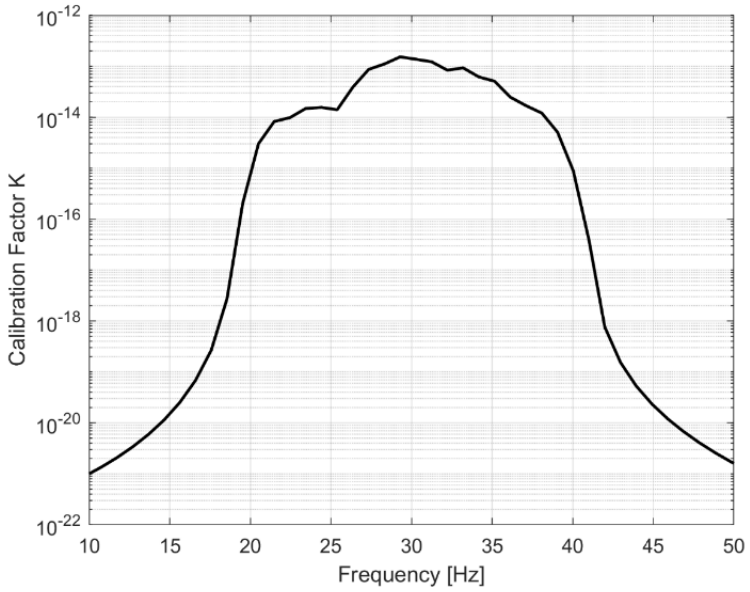


Thermal signal PSD response in the area where the strain gauge has been bonded

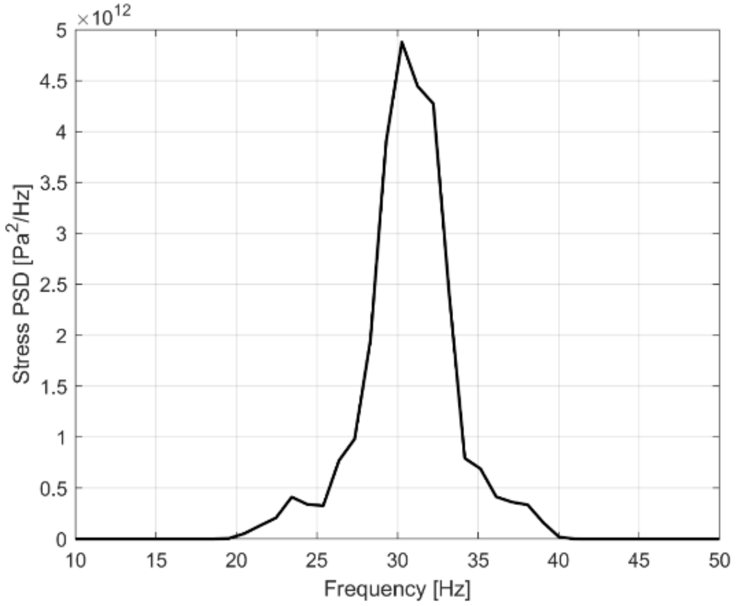
Damage evaluation in frequency domain through thermoelasticity

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

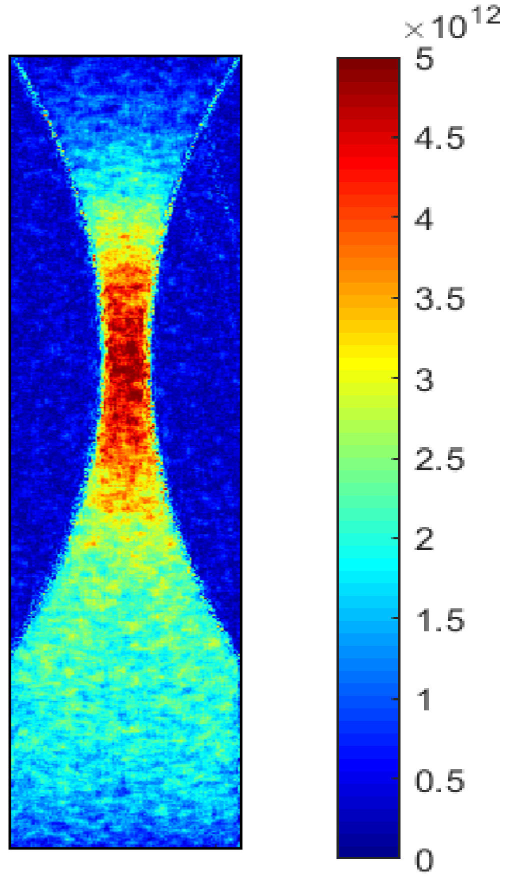
$$\Theta(\omega) = \frac{W(\omega)}{K(\omega)}$$



Calibration function $K\ (\omega)$



Stress PSD $\Theta(\omega)$



Stress PSD response map
[Pa^2/Hz]

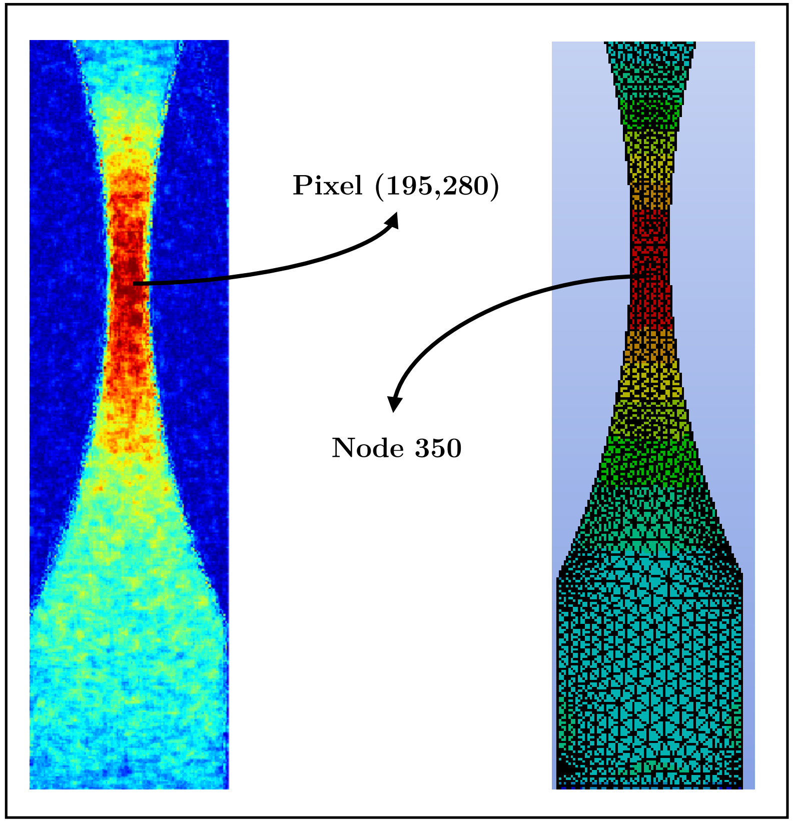
Damage evaluation in frequency domain through thermoelasticity

```
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
[~ , 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);
```

MatLab app-designer code

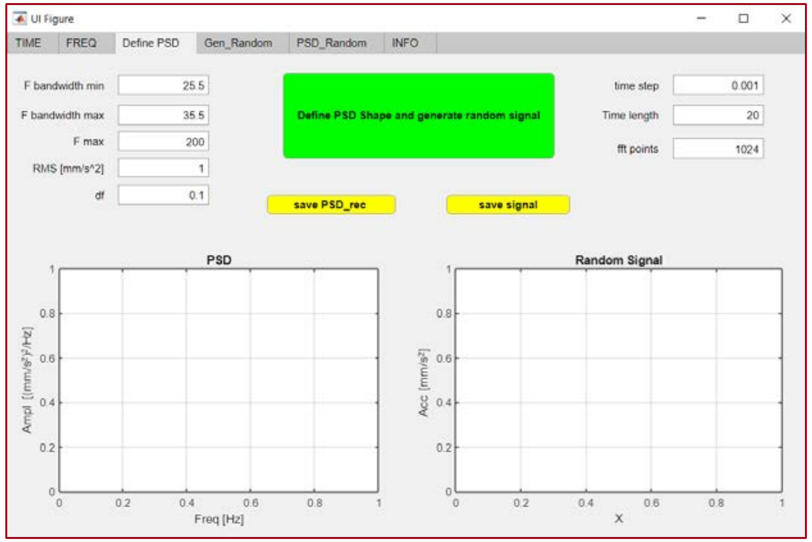
Experimental Pixel (195,280)	**Numerical** Node 350
$4.1 \cdot 10^{-9}$ s^{-1}	$4.8 \cdot 10^{-9}$ s^{-1}
$5.4 \cdot 10^{-9}$ s^{-1}	
$6.9 \cdot 10^{-9}$ s^{-1}	

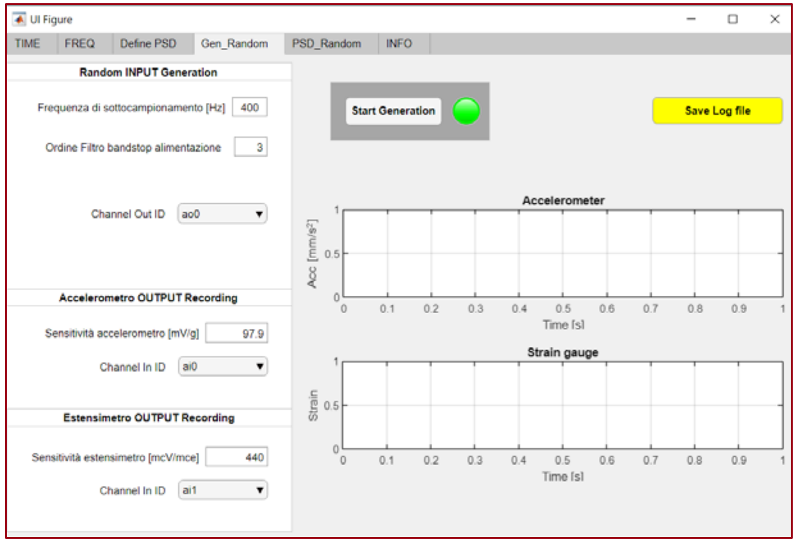
Comparison of results

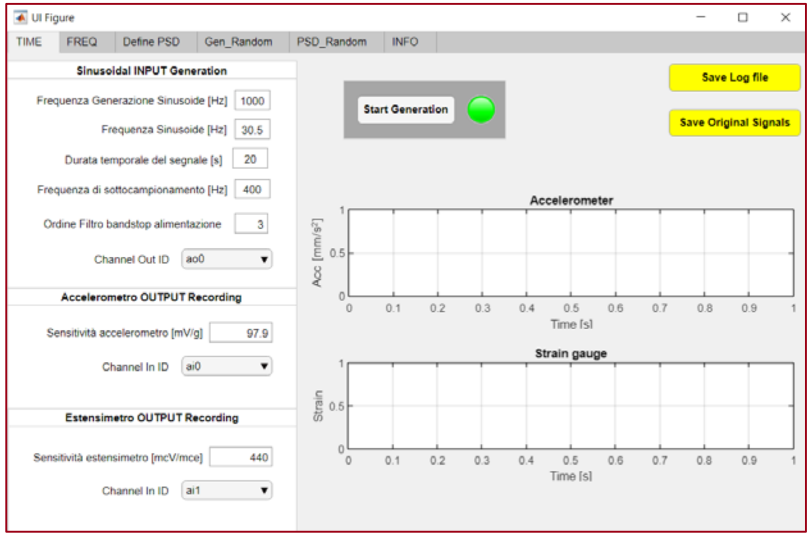


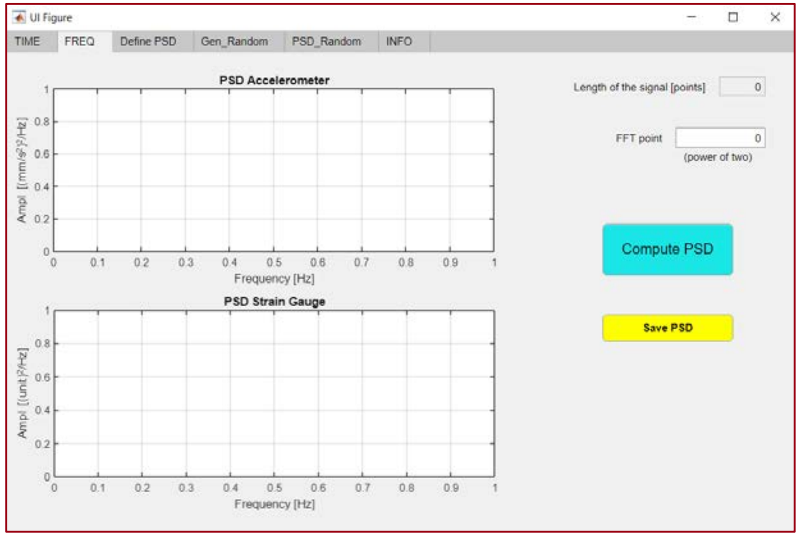
Experimental and numerical damage map [s^{-1}]

MATLAB
APP DESIGNER



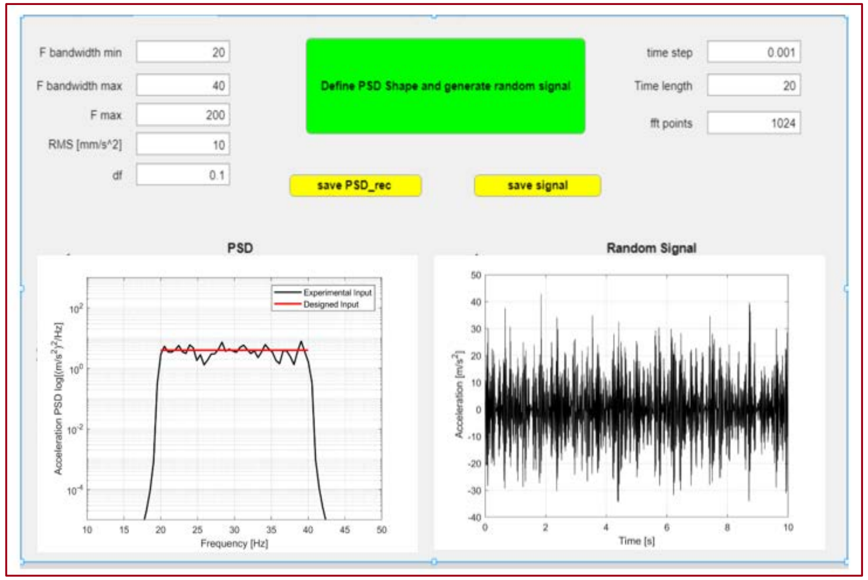


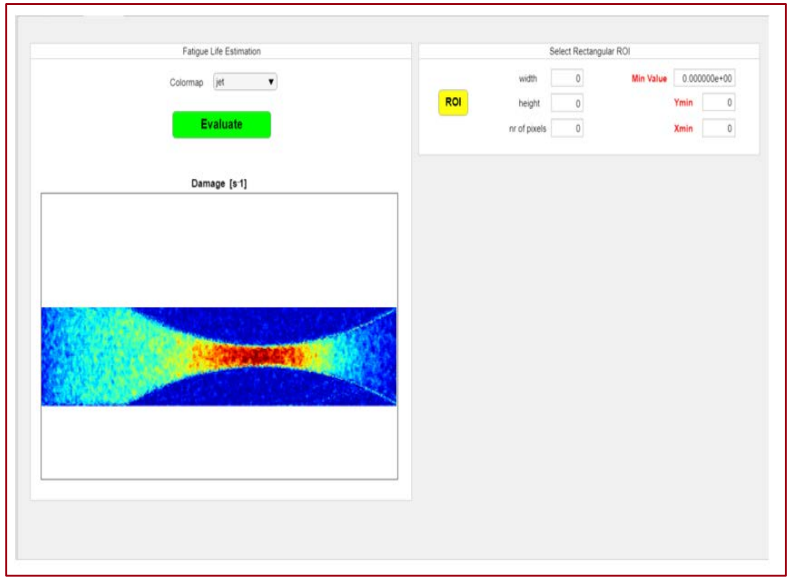


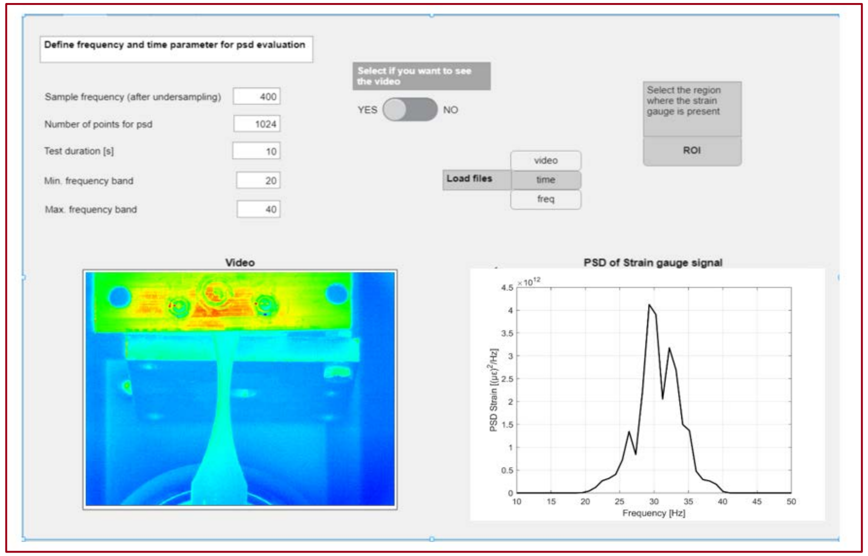


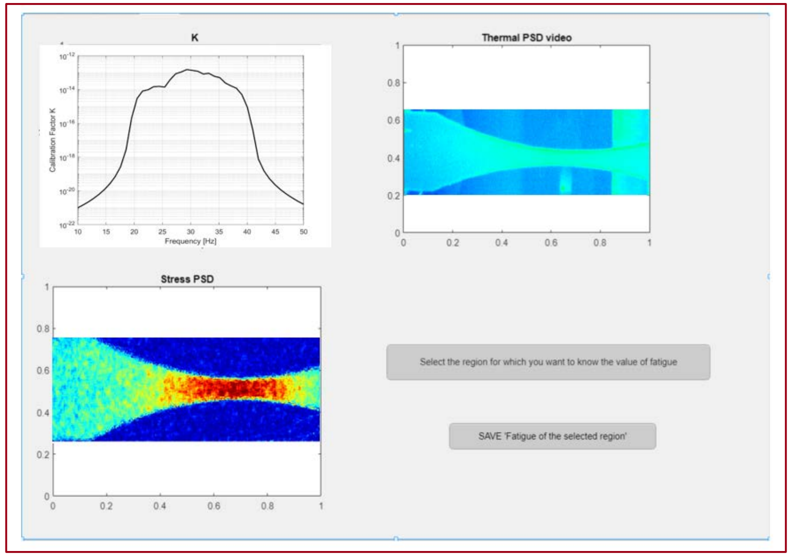
Numerical and experimental analysis

MATLAB
APP DESIGNER

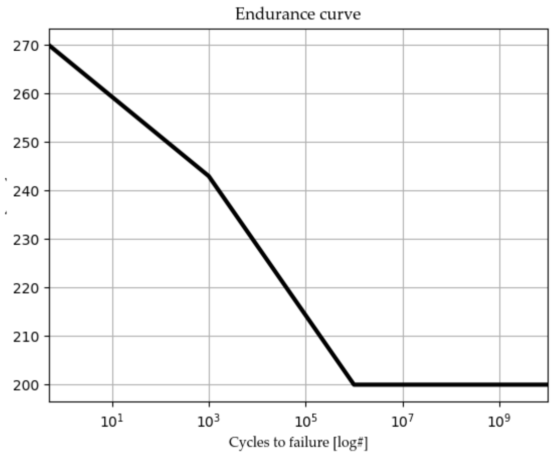


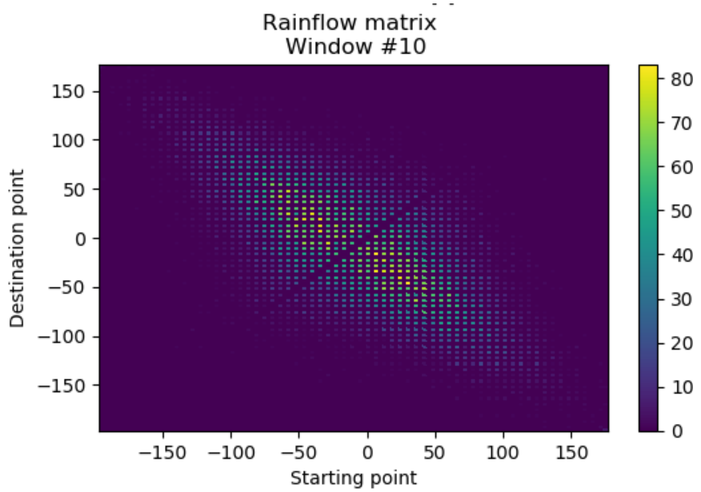


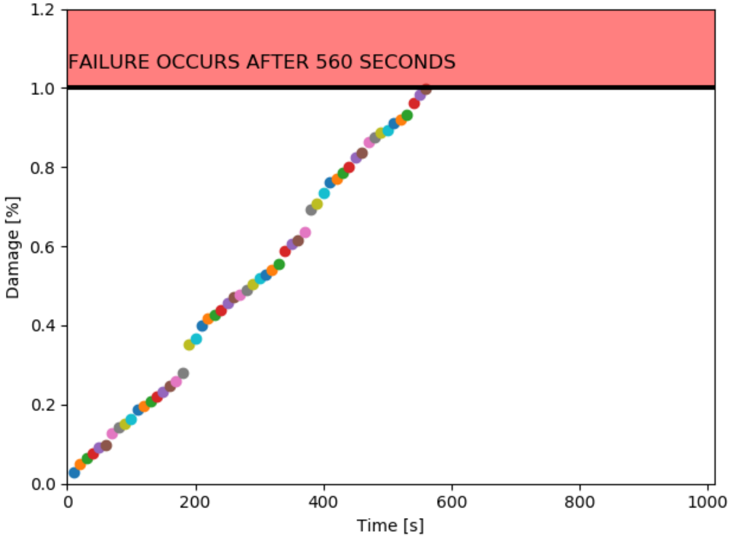


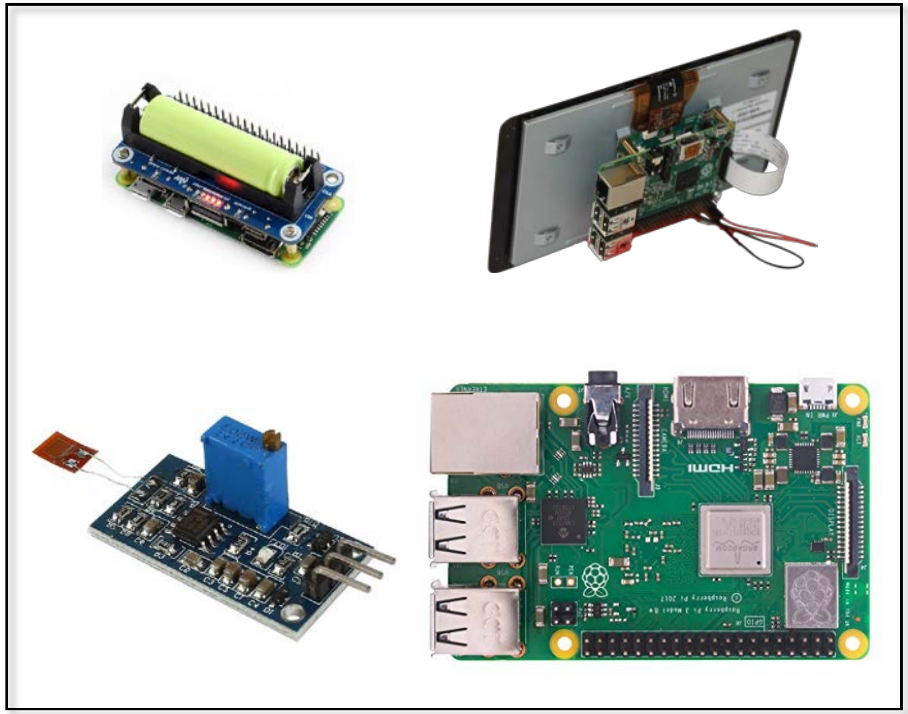


Raspberry Pi – based device for damage estimation in real-time



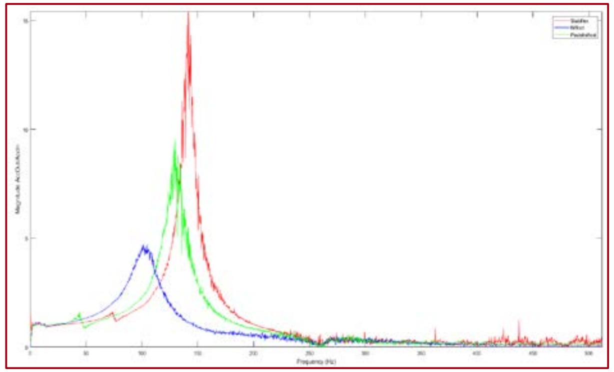


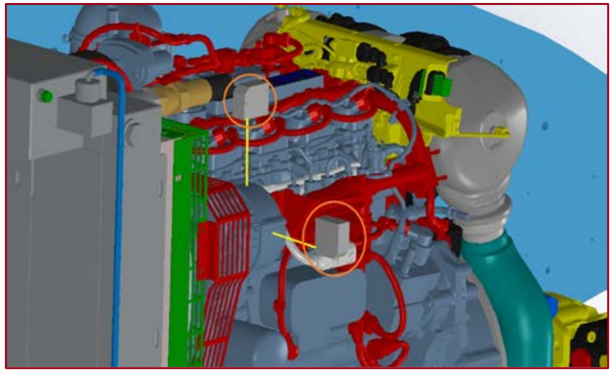




Raspberry Pi board with LCD touch screen, external power battery, strain gauge board

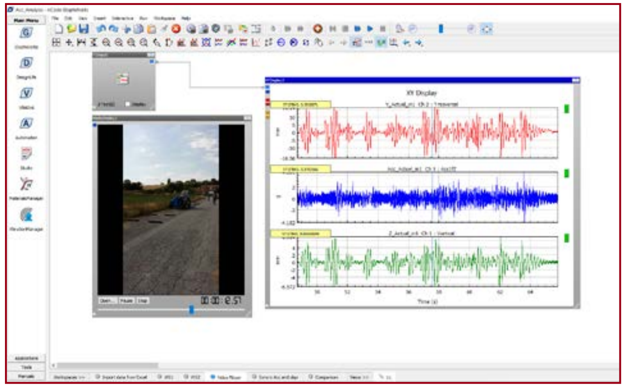
- Validation of a mathematical model that allows to predict the dynamic behavior of the engine placed on elastomeric brackets and vibration dampers





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

Gravity lowering system z60/fe



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**

Univerza *v Ljubljani*
Fakulteta za *strojništvo*
Laboratorij za dinamiko strojev in konstrukcij

Publications

- **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
Fatigue & Fracture of Engineering Materials & Structures (2019)

- **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
International Journal of Fatigue 104, 221-230 (2017)

Thanks for your attention