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UNIVERSITÀ DEGLI STUDI DI PADOVA

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

Lorenzo Capponi - 33rd Cycle

Supervisor: Prof. Gianluca Rossi

06/11/2020

Presentation

Lorenzo Capponi

April 16th 1991, Perugia

Background:

- Bachelor's degree at the DI of the University of Perugia (2014)
- Erasmus at the LADISK of the University of Ljubljana (2016-2017)
- Master's degree at the DI of the University of Perugia (2017)
- Visiting PhD student at the LADISK of the University of Ljubljana (2019-2020)

Admission to final exam:

- PhD degree at the CISAS G. Colombo of the University of Padova (in progress)

Overview

- Research goals
- Thermoelasticity-based modal damage identification
    - Theory
        - Thermoelasticity
        - Structural dynamics in frequency domain
        - Fatigue damage evaluation
        - Modal damage using thermoelasticity
    - Experiments
        - Setup
        - Modal analysis
        - Excitation
    - Results
- Additional research outputs
    - Side projects
    - Papers and conferences
- Conclusions

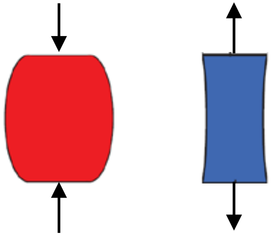
Research goals

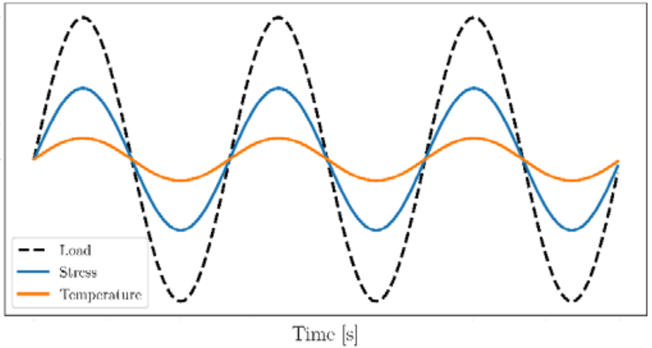
- Development of a new measurement method using image-based and non-contact techniques
- Introduction of measurement techniques in Terex industry processes
- Software development
- Production of scientific papers
- Participation at conferences and scientific events
- National and international collaborations

Thermoelasticity

Adiabatic process, Linearity, Homogeneity, Elasticity, Isotropy

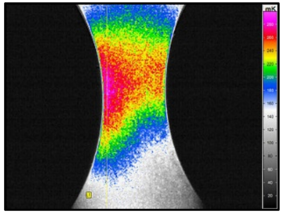
Similar effect for gasses and solids:





$$tr\begin{pmatrix} \Delta\sigma_{xx} & \Delta\sigma_{xy} & \Delta\sigma_{xz} \\ \Delta\sigma_{yx} & \Delta\sigma_{yy} & \Delta\sigma_{yz} \\ \Delta\sigma_{zx} & \Delta\sigma_{zy} & \Delta\sigma_{zz} \end{pmatrix} = -\Delta T \, \frac{\rho C_\sigma}{T_0 \alpha} \Rightarrow \Delta\sigma \propto \Delta T$$

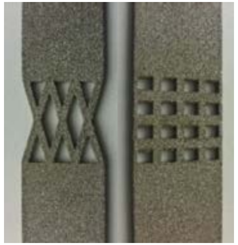
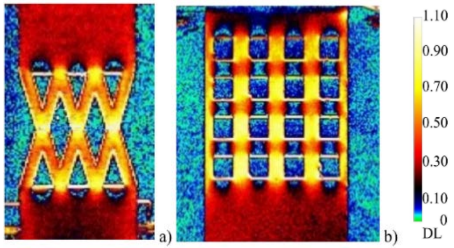
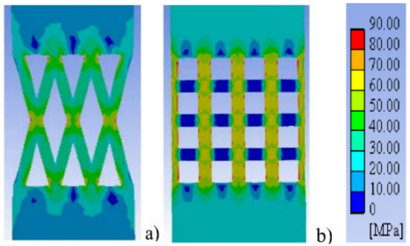
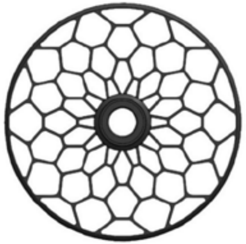
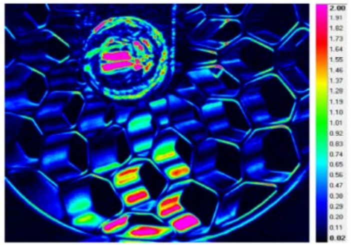
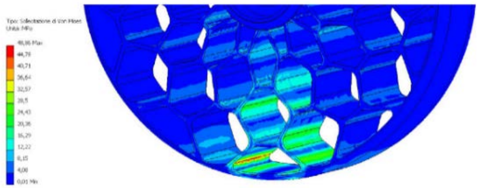
$$K_m = \frac{\rho C_\sigma}{T_0 \alpha} = \frac{\Delta T_{avg}(1-\nu)}{E \, \Delta\epsilon}$$



ρ = Density [kg/m^3]
C_σ = Specific heat at constant pressure [K J/kg]
T_0 = Ambient temperature [K]
α = Thermal coefficient expansion coefficient [1/K]
ΔT_{avg} = Averaged temperature on strain-gauge area [K]
ν = Poisson's ratio
$\Delta\epsilon$ = Measured reference strain [ϵ]
E = Young Modulus [Pa]

Über die specifische warme fester korper, insbesondere der metalle
W. Weber; Annalen der Physik (1839)
On the Dynamical Theory of Heat
W. Thomson; Earth and Environmental Science Transactions of The Royal Society of Edinburgh (1853)

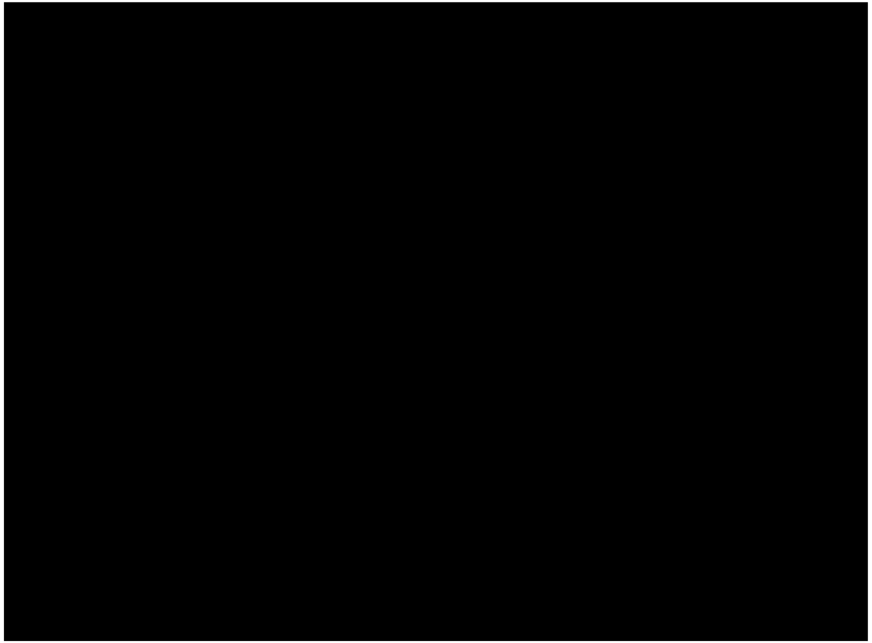
PRIN Project 2015-2020: Experimental verification of stress distribution on complex structures realized using additive manufacturing technologies

	Model	Experiments	Numerical
Trabecular structures			
Airless wheel prototype			

Investigating additive manufactured lattice structures: a multi-instrument approach
G. Allevi, L. Capponi, G.. Rossi et al.; IEEE (2019)
Structural Characterization of Complex Lattice Parts by Means of Optical Non-Contact Measurements
R. Montanini, G. Rossi, A. Quattrocchi, D. Alizzio, L. Capponi, R. Marsili, T. Tocci; IEEE (2020)

Applications

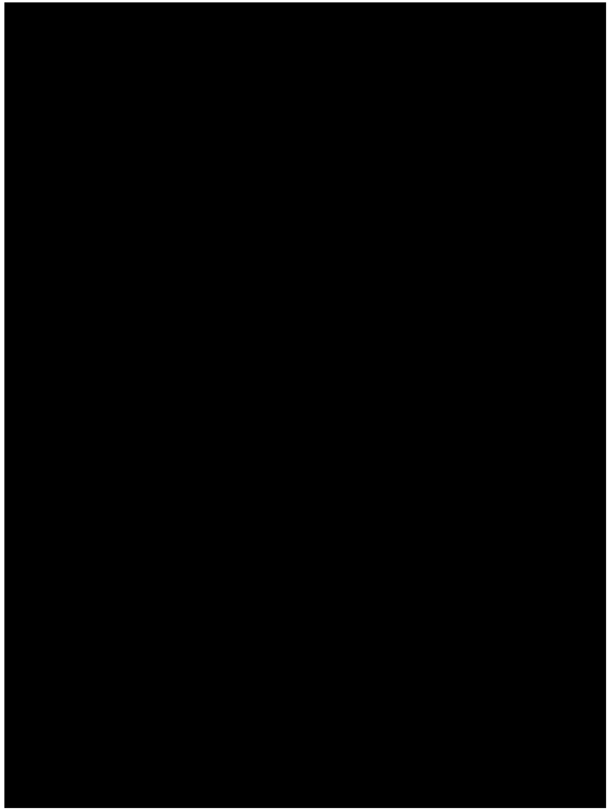
Stress distribution identification on a lifting machinery welded component using thermoelasticity



Thermoelasticity-based stress identification on scaled lifting machinery components

Genie
A TEREX BRAND

Experimental tests on CFRP robot for the online-monitoring of San Giorgio's Bridge

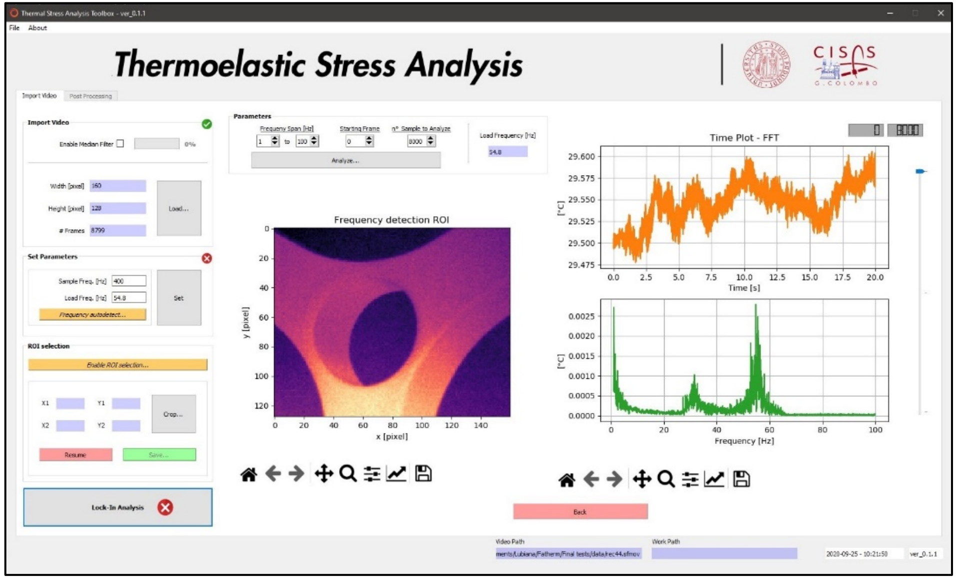


CAMOZZI

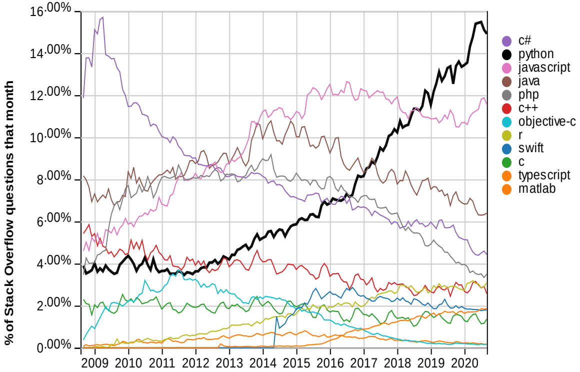
iit ISTITUTO ITALIANO DI TECNOLOGIA

Thermoelasticity and arUCO markers-based model validation of polymer structure: application to San Giorgio's bridge online-monitoring CFRP robot
L. Capponi, T. Tocci, M. D'Imperio, S. Haider, M. Scaccia, F. Cannella, G. Rossi (In Press)

Open-source software development



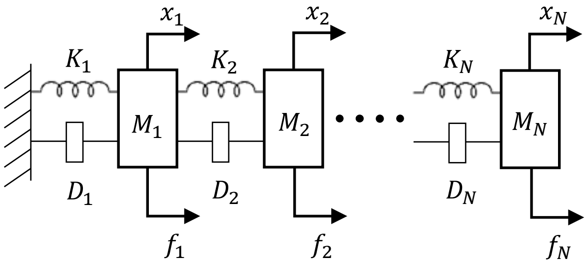
- **pysfmov**: Allows to get raw data and metadata from thermal video saved from FLIR camera software
- **pyLIA**: Performs digital lock-in analysis, giving amplitude and phase of thermoelastic signal
- **ThermCoeff**: Allows the thermoelastic coefficient identification by means of strain-gauge calibration procedure
- **IR_FLife**: Complete package for thermoelasticity-based modal damage identification



Thermoelasticity-based analysis: collection of python packages
L. Capponi; Zenodo (2020)

Structural dynamics in frequency domain

$$M\ddot{x}(t) + D\dot{x}(t) + Kx(t) = f(t)$$



$$X(\omega) = (K + \omega D - \omega^2 M)^{-1}F(\omega) = H(\omega)F(\omega)$$

$$H(\omega) = \Phi[\omega_r^2(1+\eta_r) - \omega^2]^{-1}\Phi^T$$

$$X_s(\omega) = \Phi^s[\omega_r^2(1+\eta_r) - \omega^2]^{-1}\Phi^T F(\omega) = H_{sf}(\omega)F(\omega)$$

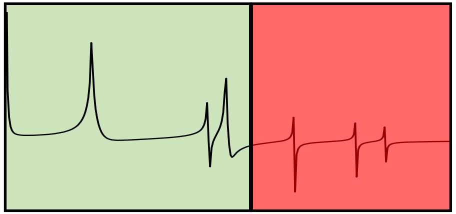
Discrete Fourier Transform (DFT)	Power Spectral Density (PSD)
$X(\omega) = \sum_{n=0}^{N-1} X_n exp\left(-\mathrm{i}\frac{n\omega}{N}\right)$	$S_{xx}(\omega) = \frac{1}{q}\sum_{u=1}^{q}\frac{1}{W}\lvert X_{T_{wu}}(\omega)\rvert^2$

Frequency Response Function:

$$H_{sf}(\omega) = \sum_{r=1}^{N} H_{sf}^r(\omega) = \sum_{r=1}^{N}\frac{X_s^r(\omega)}{F(\omega)}$$

Modal reduction:

$$\widetilde{H}_{sf}(\omega) = \sum_{r=1}^{m<N} H_{sf}^r(\omega)$$



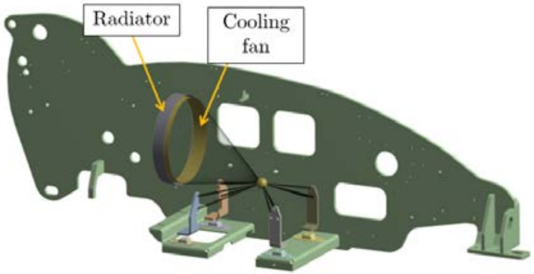
Stress response Power Spectral Density:

$$\tilde{\boldsymbol{S}}_{ss}(\boldsymbol{\omega}) = \sum_{r=1}^{m<N}\tilde{\boldsymbol{S}}_{ss}^{r}(\boldsymbol{\omega}) = \sum_{r=1}^{m<N}\boldsymbol{H}_{sf}^{r}(\boldsymbol{\omega})\cdot\boldsymbol{S}_{ff}(\boldsymbol{\omega})\cdot\boldsymbol{H}_{sf}^{r*T}(\boldsymbol{\omega})$$

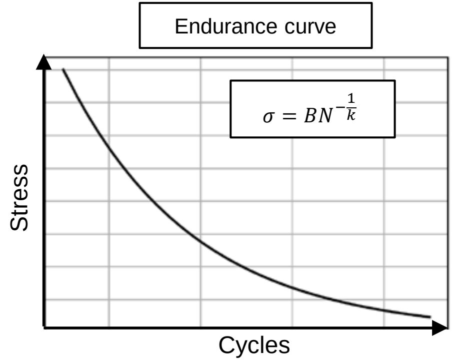
Vibration Fatigue by Spectral Methods: From Structural Dynamics to Fatigue Damage
J. Slavic, M. Mršnik, M. Cesnik, J. Javh, and M. Boltežar, Elsevier (2020)
Theoretical and experimental modal analysis
N. M. M. Maia and J. M. M. Silva ; Research Studies Press (1997)

Applications

Engine suspension experimental characterization for cooling fan and radiator damageability reduction



Damage evaluation



Palmgren-Miner: $$\bar{D} = \sum_i \bar{D}_i = \sum_i \frac{n_i}{N_i}$$

Tovo-Benasciutti: $$\bar{D}_{TB} = \left[b + (1-b)\alpha_2^{k-1}\right]\bar{D}_{NB} = \boldsymbol{\bar{D}_{TB}\left(\tilde{S}_{ss}(\omega), B, k\right)}$$

Dirlik: $$\bar{D}_{DK} = C^{-1}\nu_p m_0^{\frac{k}{2}}\left[G_1 Q^k \Gamma(1+k) + \left(\sqrt{2}\right)^k \Gamma\left(1+\frac{k}{2}\right)\left(G_2|R|^k + G_3\right)\right] = \boldsymbol{\bar{D}_{DK}\left(\tilde{S}_{ss}(\omega), B, k\right)}$$

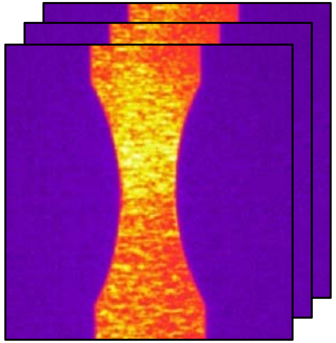
$$\boldsymbol{x_m} = \frac{m_1}{m_0}\left(\frac{m_2}{m_4}\right)^{\frac{1}{2}} \qquad \boldsymbol{\Gamma(z)} = \int_0^\infty t^{z-1}e^{-t}\mathrm{d}t \qquad \boldsymbol{\bar{D}_{NB}} = \nu_p C^{-1}\alpha_2\left(\sqrt{2m_0}\right)^k \Gamma\left(1+\frac{k}{2}\right) \qquad \boldsymbol{m_i} = \int_0^\infty \omega^i \tilde{S}_{ss}(\omega)\mathrm{d}\omega$$

$$\boldsymbol{R} = \frac{\alpha_2 - x_m - G_1^2}{1-\alpha_2-G_1+G_1^2} \qquad \boldsymbol{\nu_p} = \frac{1}{2\pi}\sqrt{\frac{m_4}{m_2}} \qquad \boldsymbol{G_1} = \frac{2(x_m-\alpha_2^2)}{1+\alpha_2^2} \qquad \boldsymbol{G_2} = \frac{1-\alpha_2\, G_1 + G_2}{1-R} \qquad \boldsymbol{\alpha_i} = \frac{m_i}{\sqrt{m_0 m_{2i}}} \qquad \boldsymbol{G_3} = 1 - G_1 - G_2$$

$$\boldsymbol{Q} = \frac{1.25(\alpha_2 - G_3 - G_2 R)}{G_1} \qquad \boldsymbol{b} = \frac{(\alpha_1-\alpha_2)(1.112(1+\alpha_1\alpha_2-\alpha_1-\alpha_2)^{2.11\alpha_2}+\alpha_1-\alpha_2}{(\alpha_2-1)^2}$$

Spectral methods for lifetime prediction under wideband stationary random processes
D. Benasciutti and R. Tovo; International Journal of Fatigue (2013)
Application of computers in fatigue analysis,
T. Dirlik; PhD thesis, University of Warwick (1985).
Frequency-domain methods for a vibration fatigue-life estimation: Application to real data
M. Mršnik, J. Slavic, and M. Boltežar; International Journal of Fatigue (2013)

Damage evaluation using thermal information

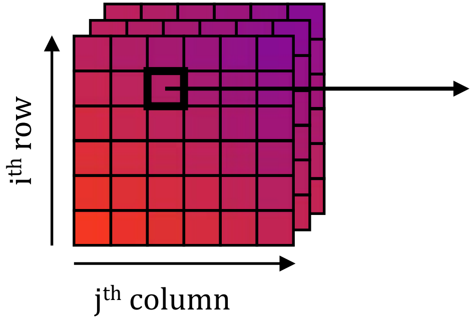


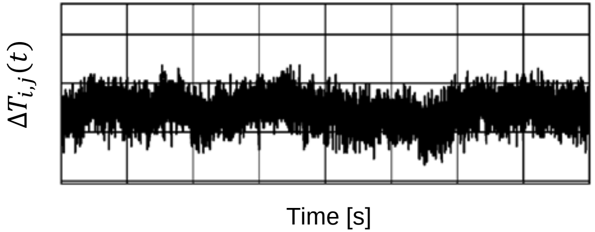
$$\tilde{S}_{ss\,i,j}(\omega) = \frac{1}{q}\sum_{u=1}^{q}\frac{1}{W}\left|\Delta\sigma_{i,j}(t)\right|^2 = \frac{1}{q}\sum_{u=1}^{q}\frac{1}{W}\left|\frac{\Delta T_{i,j}(t)}{K_m}\right|^2$$

$$\Delta\sigma_{i,j}(t) = \frac{\Delta T_{i,j}(t)}{K_m}$$

$$\bar{D}_{TB_{i,j}} = \bar{D}_{TB_{i,j}}\left(\tilde{S}_{ss\,i,j}(\omega), B, k\right)$$

$$\bar{D}_{DK_{i,j}} = \bar{D}_{DK_{i,j}}\left(\tilde{S}_{ss\,i,j}(\omega), B, k\right)$$



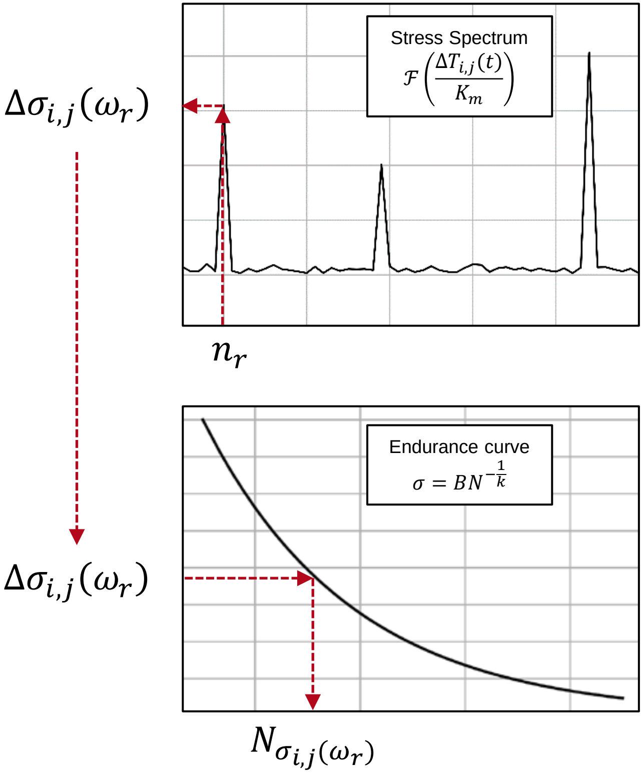


Modal damage using thermoelasticity

Proposed modal approach:

$$\bar{D} = \sum_{r=1}^{N} \bar{D}_r = \sum_{r=1}^{N} \frac{n_r}{N_{\sigma_{i,j}(\omega_r)}}$$

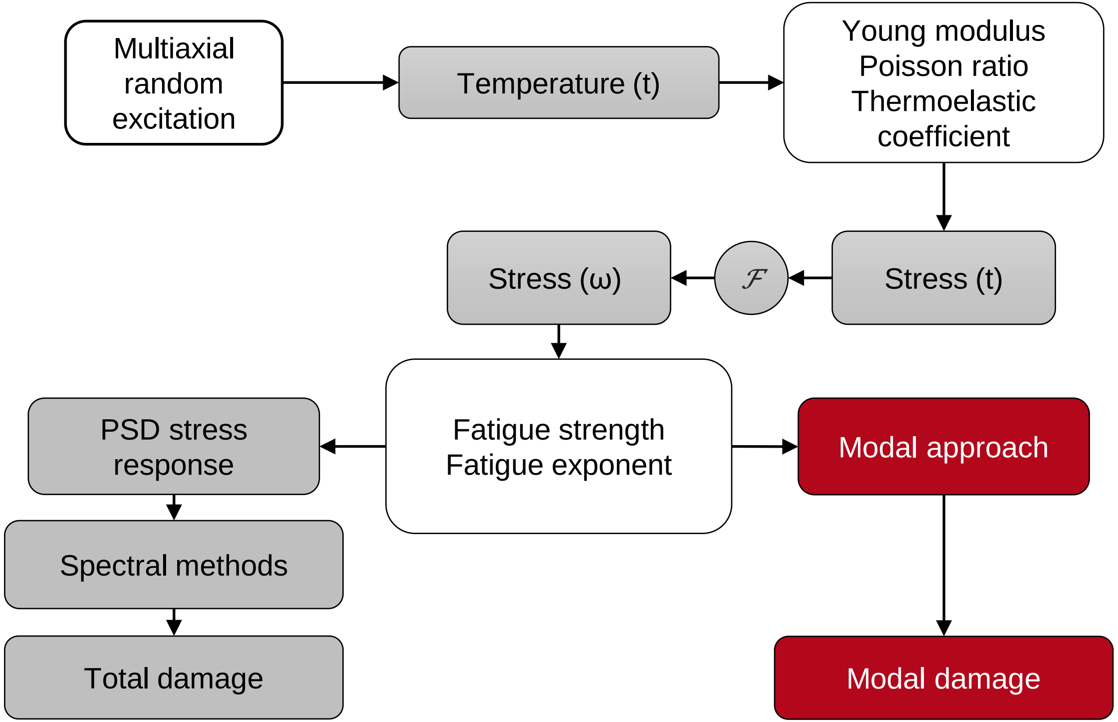
$$n_r = \frac{\omega_r}{2\pi} \qquad N_{\sigma_{i,j}} = \left(\frac{B}{\mathcal{F}\left(\frac{\Delta T_{i,j}(t)}{K_m}\right)} \right)^k$$



Damage intensity caused by each considered mode:

$$\boldsymbol{\bar{D}_r = n_r \left(\frac{1}{B}\, \mathcal{F}\left(\Delta\sigma(\omega_r)\right) \right)^k = n_r \left(\frac{1}{B} \mathcal{F}\left(\frac{\Delta T_{i,j}(t)}{K_m} \right) \right)^k}$$

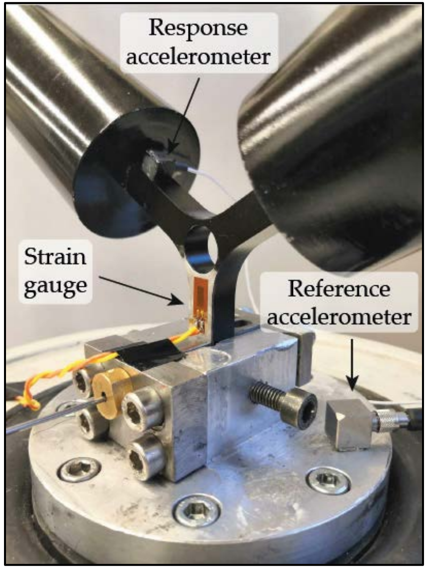
Modal damage using thermoelasticity



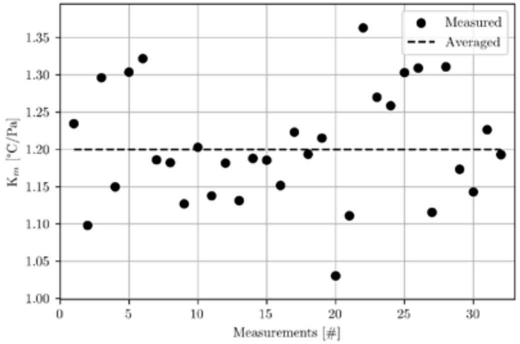
Thermoelasticity-based modal damage identification

Setup

Material	A-S8U3
Young Modulus	$75 \cdot 10^3$ [MPa]
Density	2710 [kg/m^3]
Poisson ratio	0,33
Fatigue exponent	6,51
Fatigue strength	800,26 [MPa]
Thermoelastic coefficient	$1{,}2 \cdot 10^{-8} \pm 15\%$ [°C/Pa]



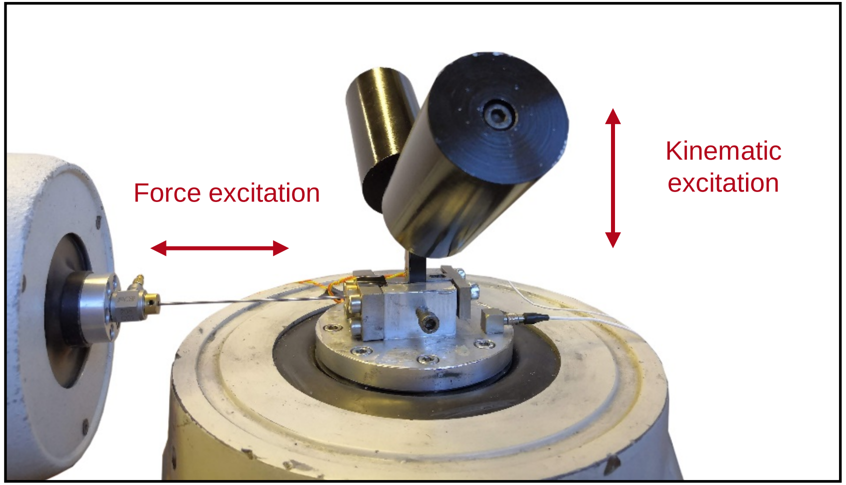
Strain-gauge calibration

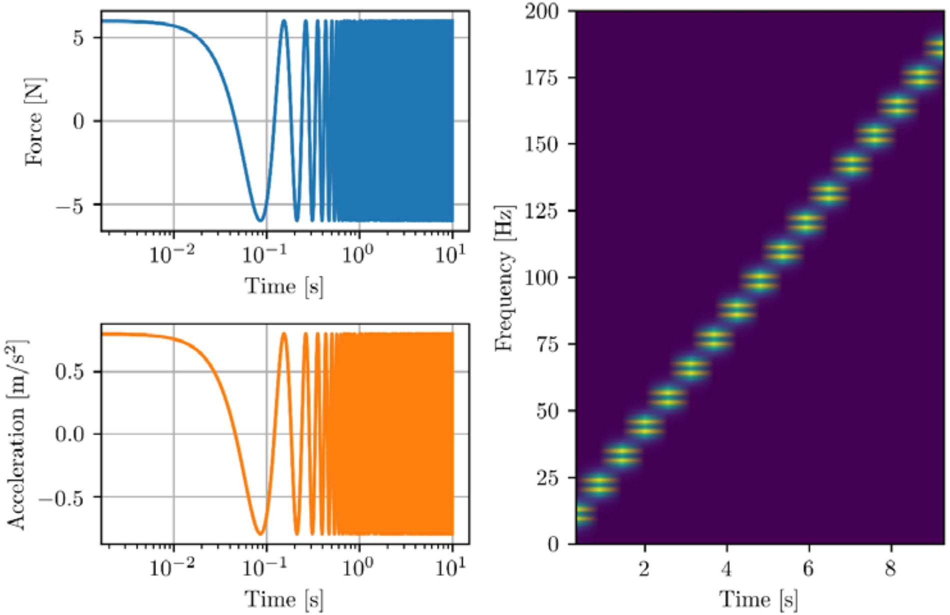


$$K_m = \frac{\Delta T_{avg}(1-\nu)}{E\,\Delta\epsilon} = 1{,}2 \cdot 10^{-8} \pm 15\%$$

Uninterrupted and accelerated vibrational fatigue testing with simultaneous monitoring of the natural frequency and damping
M.Česnik, J. Slavič and M. Boltežar; Journal of Sound and Vibration (2012)
Non-stationarity index in vibration fatigue: Theoretical and experimental research;
L. Capponi, M. Česnik, J. Slavič, F. Cianetti, M. Boltežar; International Journal of Fatigue (2017)
Vibration fatigue using modal decomposition
M. Mršnik, J. Slavič and M. Boltežar; Mechanical Systems and Signal Processing, Vol. 98, p. 548-556 (2018)

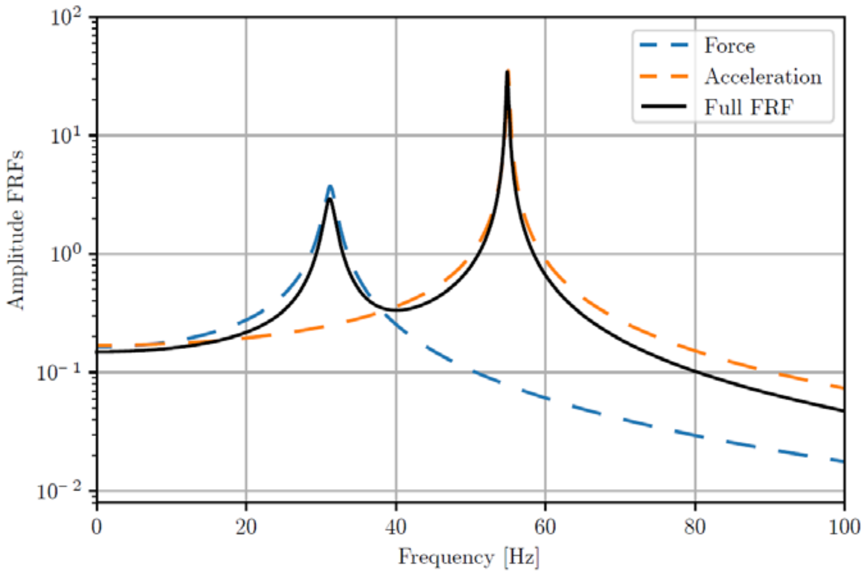
Modal analysis





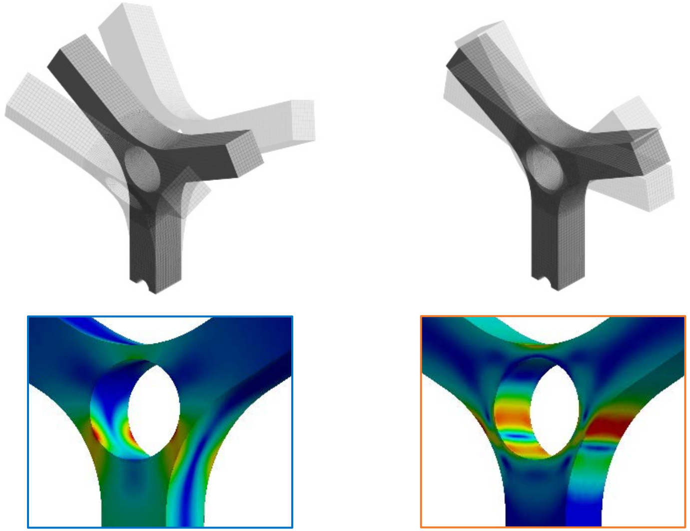
Linear sine-sweep in 10-200 Hz range

Modal analysis



Reconstructed FRF

Mode shapes and modal stress

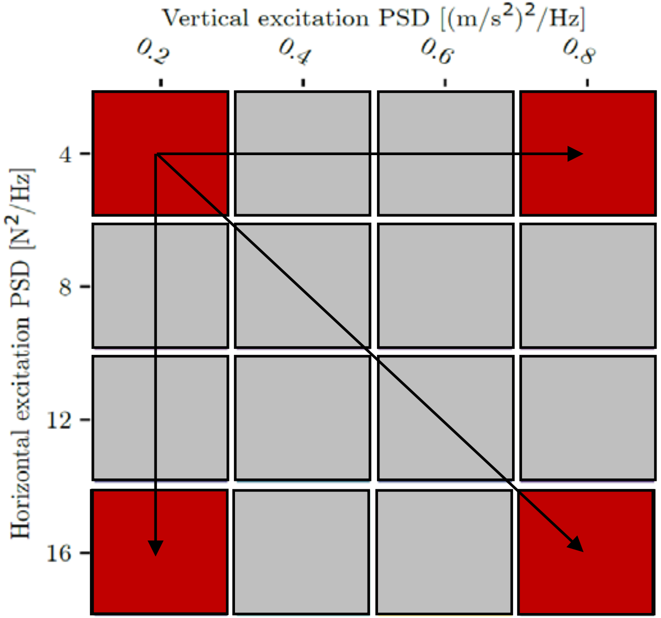


$f_1 \cong 33$ [Hz]

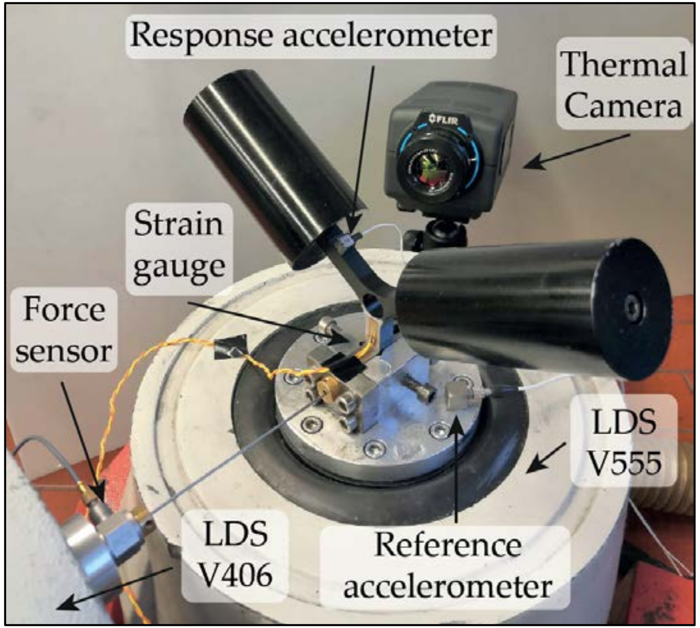
$f_2 \cong 55$ [Hz]

Thermoelasticity-based modal damage identification

Excitation



16 experimental combinations

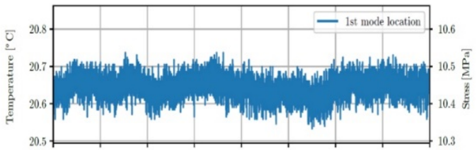


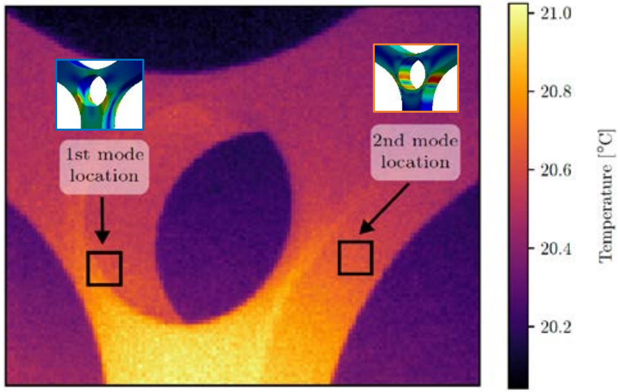
Thermal camera: FLIR A6751sc
NETD: < 18 mK
Infrared detector: MWIR Indium Antimonide
Dynamic range: 14-bit
Sampling frequency: 400 Hz
Resolution: 128 x 160 pixels

Thermoelasticity-based modal damage identification

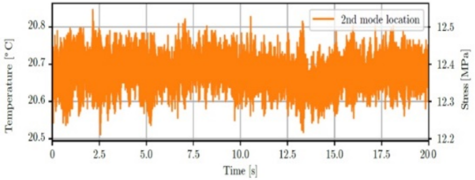
Excitation

Temperature-stress time-history



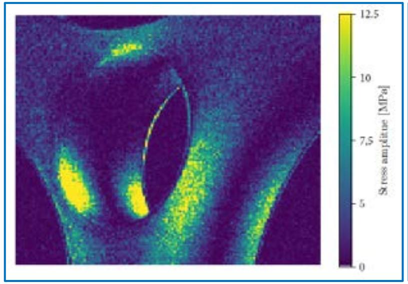


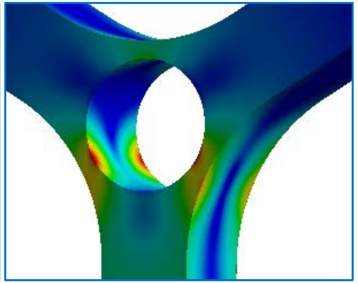
Temperature-stress time-history

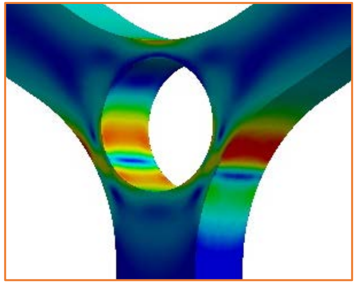


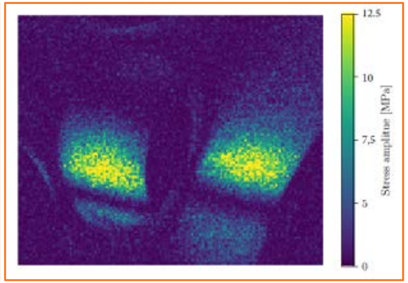
$f_1 \cong 33$ [Hz]

$f_2 \cong 55$ [Hz]



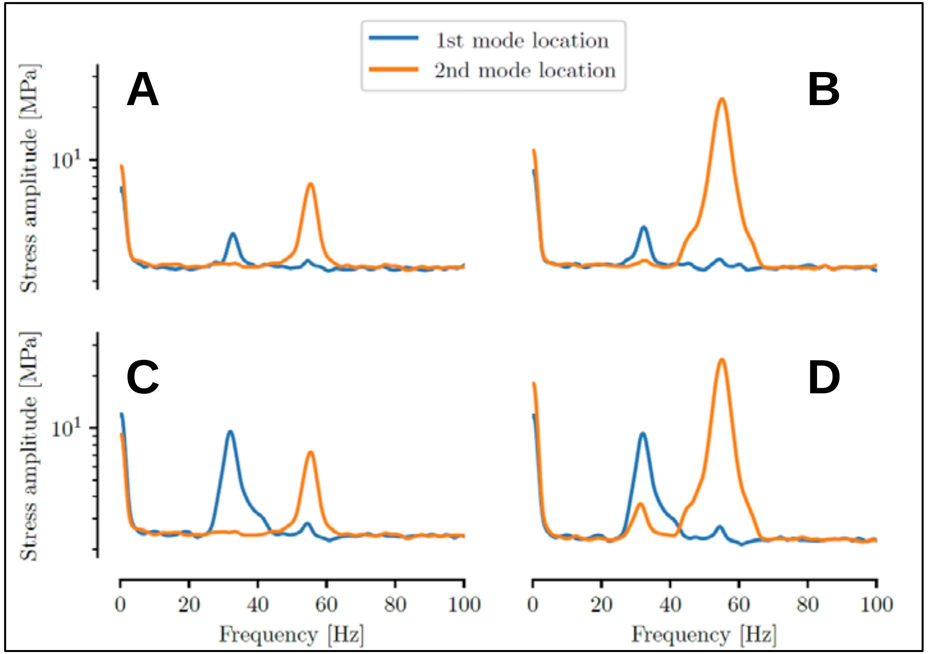


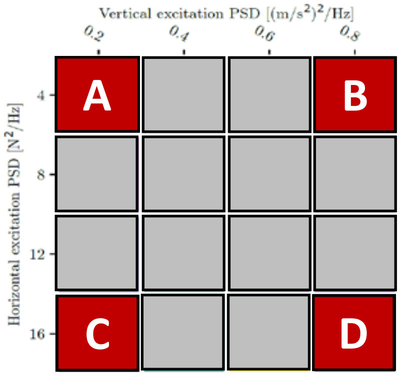




Thermoelasticity-based modal damage identification

Excitation



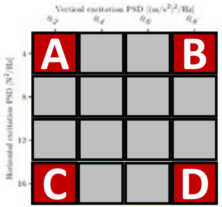


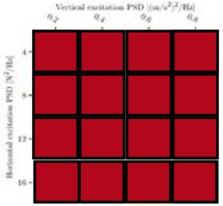
Tovo-Benasciutti: $\overline{D}_{TB_{i,j}} = \overline{D}_{TB_{i,j}}\left(\frac{1}{q}\sum_{u=1}^{q}\frac{1}{T_w}\left|\Delta\sigma_{Twu_{i,j}}(\omega)\right|^2, B, k\right)$

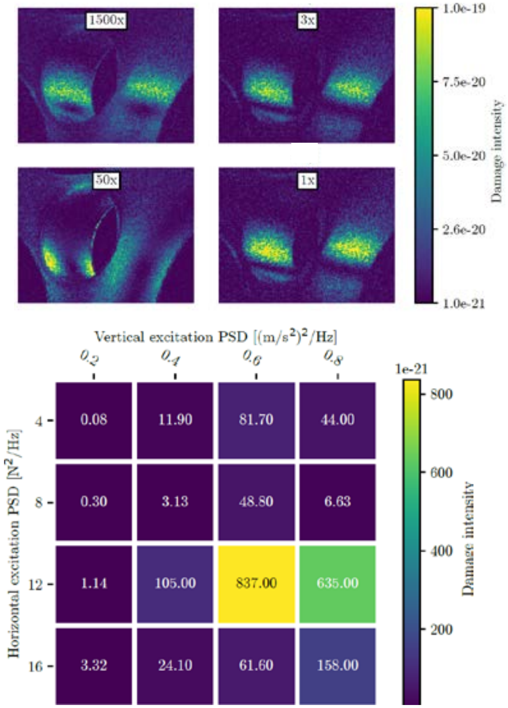
Dirlik: $\overline{D}_{DK_{i,j}} = \overline{D}_{DK_{i,j}}\left(\frac{1}{q}\sum_{u=1}^{q}\frac{1}{T_w}\left|\Delta\sigma_{Twu_{i,j}}(\omega)\right|^2, B, k\right)$

Modal damage: $\overline{D}_{i,j} = \sum_r \overline{D}_{r_{i,j}} = \sum_r n_r\left(\frac{1}{B}\,\mathcal{F}\left(\Delta\sigma_{i,j}(\omega_r)\right)\right)^k$

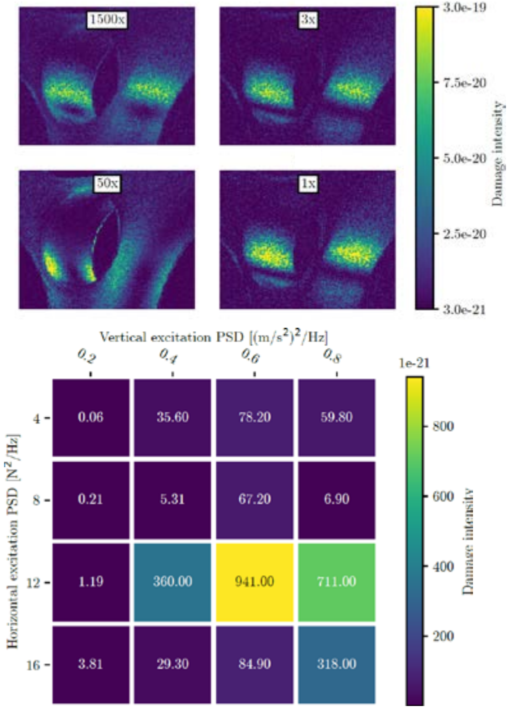
Thermoelasticity-based modal damage identification







Tovo-Benasciutti



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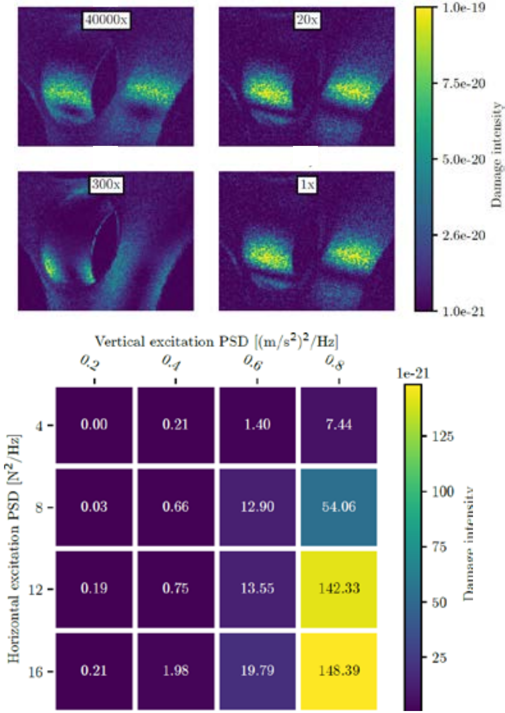
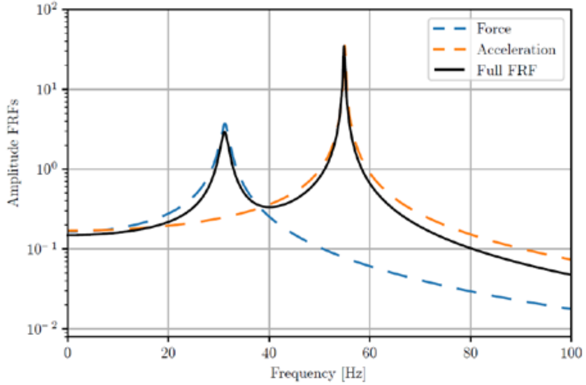


Modal damage

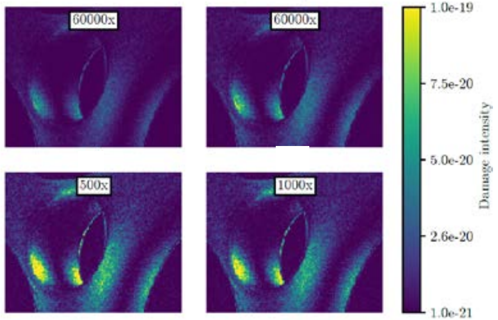
Thermoelasticity-based modal damage identification

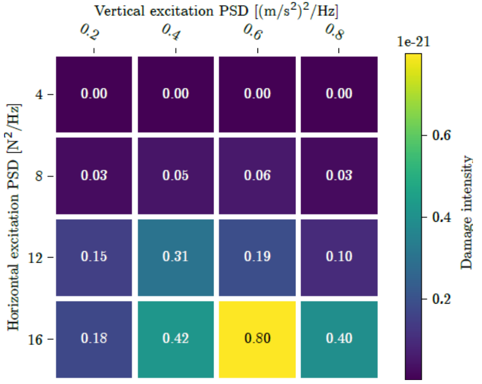
Results

$$\bar{D}_{i,j} = \sum_{r} \bar{D}_{r_{i,j}} = \bar{D}_{1_{i,j}} + \bar{D}_{2_{i,j}} = \bar{D}_{(33\ Hz)_{i,j}} + \bar{D}_{(55\ Hz)_{i,j}}$$

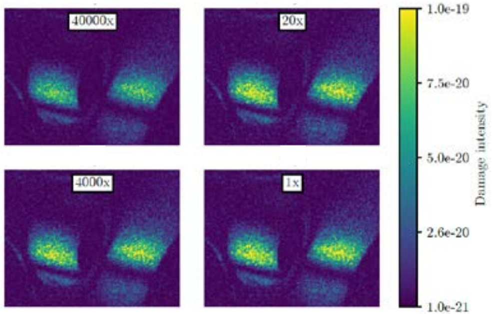


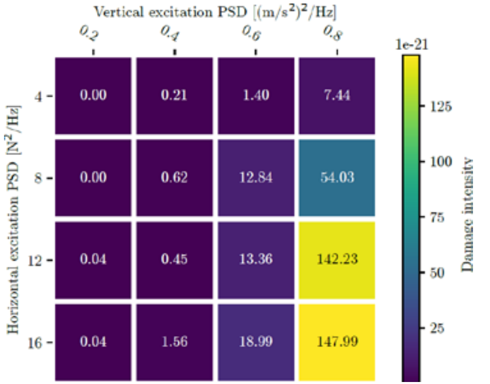
$f_1 \cong 33$ [Hz]





$f_2 \cong 55$ [Hz]





Thermoelasticity-based modal damage identification

- Spatial information
- Visual mode shape definition
- Insensitive to uncertainty even using small-dynamic-range sensor
- Modal damage information
- Robust and theoretically-supported
- Promising also for online-monitoring and off-grid applications

Additional research outputs

Side projects

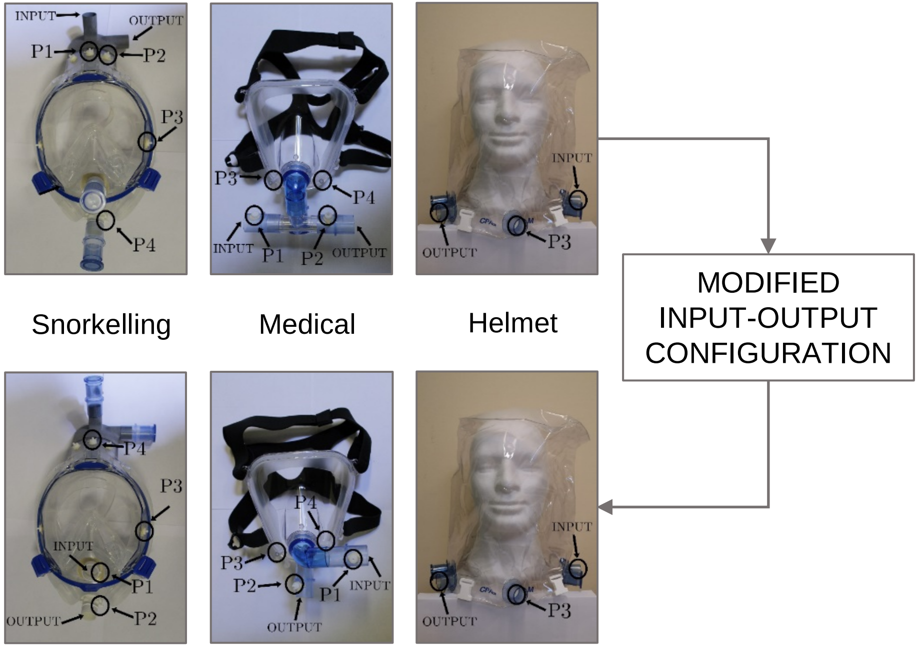
- Thermoelasticity-based experimental tests for Terex lifting machinery factory.
- Master thesis supervisor for four student's traineeships in Terex lifting machinery factory.
- Acoustic measurement in anechoic chamber for DeWalt circular saws noise reduction.
- Optimization of wood dust emission from DeWalt circular saws.
- Vibration fatigue accelerated test on Korg musical products packaging.
- Vibration fatigue test on Renzacci S.p.a. machinery components.
- Design of innovative solutions and experimental tests for SIS.Tg products.
- Design of innovative additive manufacturing solutions for Igea Pro Srl.
- Experimental tests on polymer online-monitoring robot of San Giorgio's Bridge in collaboration with Camozzi Group, Inse Berardi and Italian Institute of Technology (IIT).
- Training courses on additive manufacturing technologies for Terex Srl and TUCEP
- Training course on experimental frequency analysis for Terex Srl.
- Practical exercising in Bachelor's and Master's in Mechanical and Thermal Measurement courses at the Department of Engineering of University of Perugia.
- Scientific collaboration with 3DFIC for the development of new technologies for medical applications
- Scientific collaboration with the Laboratory for Dynamics of Machines and Structures (LADISK) of the Faculty of Mechanical Engineering of the University of Ljubljana
- Scientific collaboration in a national project on non-contact experimental characterization of trabecular structures and airless prototype realized through additive manufacturing technologies
- Scientific collaboration with medical equips for the development of optimized CPAP masks during Sars-COV-2 pandemic.

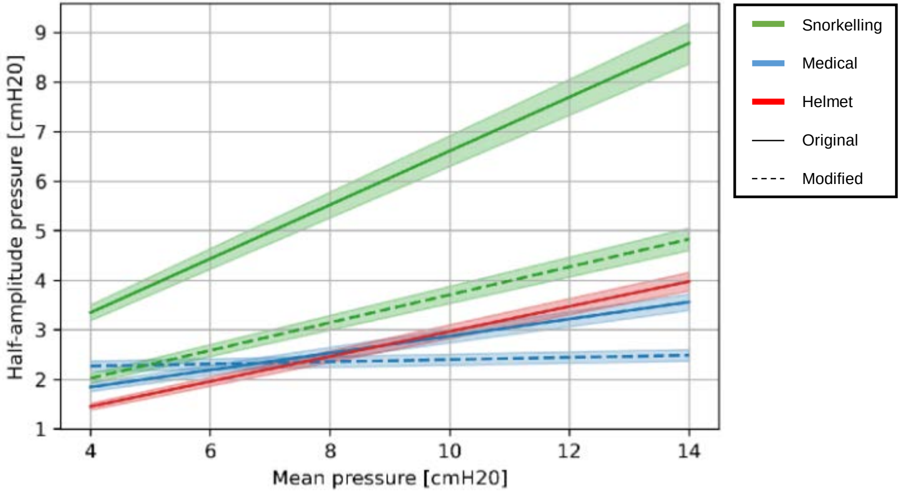
Side projects

- Theoretical and experimental analysis of lifting machinery efficiency: hydraulic and mechanical transmissions
- Theoretical and experimental verification of energy saving of an electric Gravity Lowering System
- Training courses

[redacted]

Development of optimized CPAP masks during Sars-COV-2 pandemic: snorkelling mask adapted for NIV process





Performance assessment of medical and non-medical CPAP interfaces used during the COVID-19 pandemic
M. Marini, L. Capponi et al. (In Press)

Papers and conferences

1. ***Non-stationarity index in vibration fatigue: Theoretical and experimental research***;
L. Capponi, M. Česnik, J. Slavič, F. Cianetti, M. Boltežar; International Journal of Fatigue (2017)

2. ***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 (2018)

3. ***Census Transform Based Optical Flow for Motion Detection during Different Sinusoidal Brightness Variations***;
G. Allevi, L. Casacanditella, L. Capponi, R. Marsili, G. Rossi; Journal of Physics: Conference Series (2018)

4. ***Investigating additive manufactured lattice structures: a multi-instrument approach***;
G. Allevi, L. Capponi, P. Castellini, P. Chiariotti, F. Docchio, F. Freni et al.; IEEE I2MTC (2019)

5. ***Non-stationarity and non-Gaussianity in Vibration Fatigue;***
J. Slavič, M. Česnik, L. Capponi, M. Palmieri, F. Cianetti, M. Boltežar; Sensors and Instrumentation, (2020)

6. ***Collection of experimental data for multiaxial fatigue criteria verification***;
G. Morettini, L. Capponi, C. Braccesi, F. Cianetti, S.M.J. Razavi, K. Solberg; FFEMS (2020)

7. ***Thermoelasticity-based modal damage identification***;
L. Capponi, J. Slavič, G. Rossi, M. Boltežar; International Journal of Fatigue (2020)

8. ***Structural Characterization of Complex Lattice Parts by Means of Optical Non-Contact Measurements***;
R. Montanini, G. Rossi, A. Quattrocchi, D. Alizzio, L. Capponi, R. Marsili; IEEE I2MTC (2020)

9. ***Thermoelastic stress analysis on rotating and oscillating mechanical components***;
L. Capponi, R. Marsili, G. Rossi, T. Zara; International Journal of Computational Engineering Research (IJCER) (2020)

10. ***Suction system vapour velocity map estimation through SIFT-based algorithm;***
T. Tocci, L. Capponi, R. Marsili, G. Rossi, J. Pirisinu; Journal of Physics: Conference Series (2020)

Conclusions

1st

- Learnt measurement techniques, dedicated software and improved laboratory skills
- Experience in Terex Italia Srl factory
- Deepened Thermoelasticity technique
- Educational activities

2nd

- National collaborations with industries and research groups
- Research projects in collaboration with Terex Italia Srl factory
- Educational activities
- Scientific papers and conferences

3rd

- International collaborations with industries and research groups
- Educational activities
- Visiting PhD period abroad
- Scientific papers and conferences
- PhD thesis writing

PhD

- Admission to final exam
- PhD defence
- PhD degree

Conclusions

- Development of a new measurement method using image-based and non-contact techniques
- Introduction of measurement techniques in industry processes
- Software development
- Production of scientific papers
- Participation at conferences and scientific events
- National and international collaborations

Thanks for the attention