Systemy SHM opracowane w AGH w oparciu o niskie częstotliwości

Akademia Górniczo – Hutnicza
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Plan prezentacji

1. **Monitorowanie stanu konstrukcji w oparciu o pomiary wizyjne**
2. **Implementacja filtru modalnego**

Monitorowanie stanu konstrukcji w oparciu o pomiary wizyjne

Pomiary stanów statycznych
Pomiary procesów dynamicznych

Zespół:

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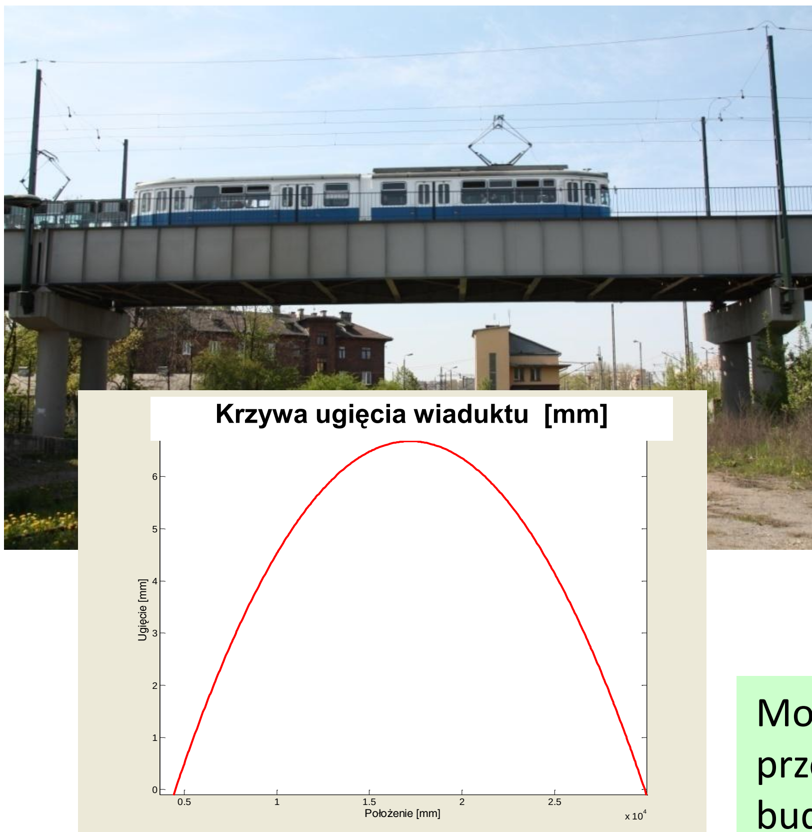
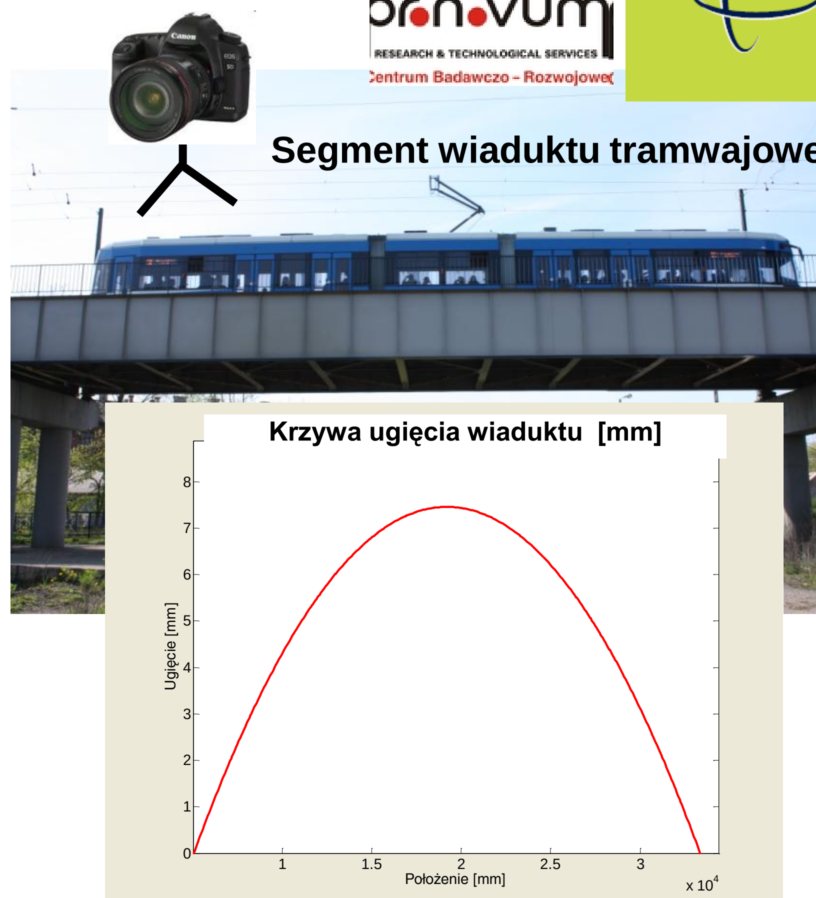
Wizyjne pomiary stanów statycznych

Tani system wykorzystujący ogólnie dostępne aparaty cyfrowe (lustrzanki) do pomiaru odkształceń konstrukcji



Segment wiaduktu tramwajowego



Monitorowane obiekty: mosty, kładki, wiadukty kominy, przęsła, dźwigary , hale, maszty, turbiny wiatrowe, budynki, rurociągi , maszyny i urządzenia

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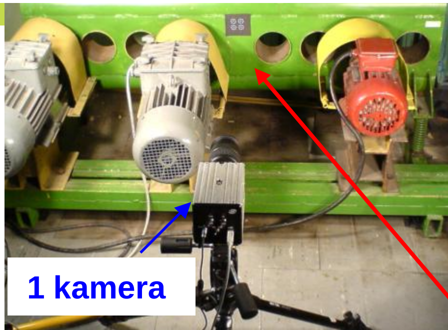
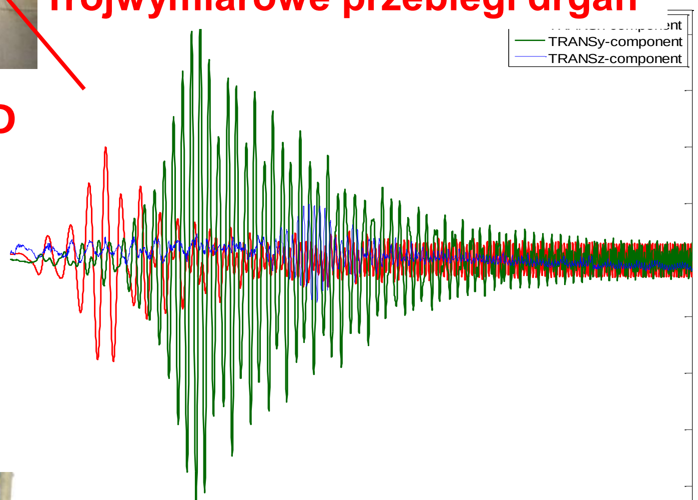
Wizyjne pomiary procesów dynamicznych

Maszyna wibracyjna

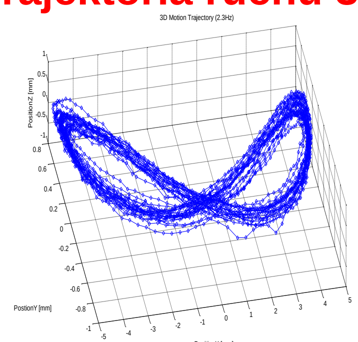


1 kamera

Trójwymiarowe przebiegi drgań

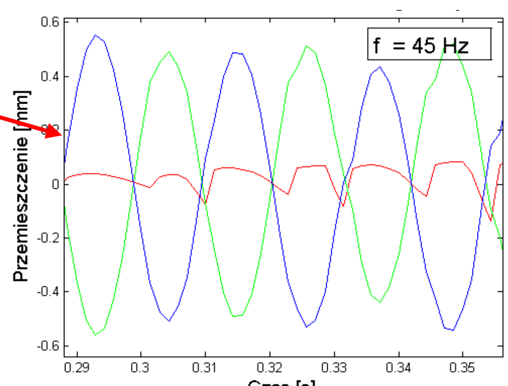


Trajektoria ruchu 3D

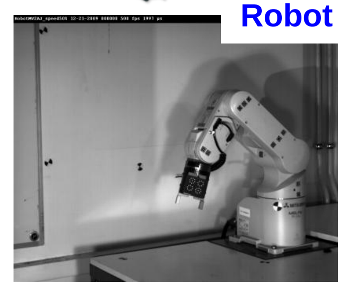


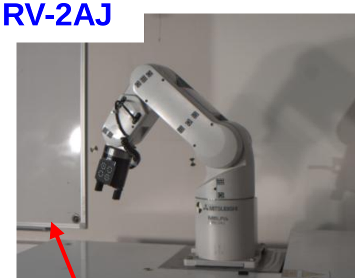
przednia Maska samochodu

Trójwymiarowe przebiegi drgań

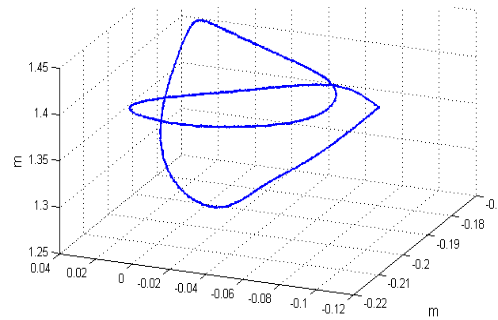


Robot RV-2AJ





3D Trajektoria ruchu chwytaka robota



Monitorowane obiekty: mosty, kładki, wiadukty kominy, przęsła, dźwigary , hale, maszty, turbiny wiatrowe, budynki, rurociągi , maszyny i urządzenia

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Lockin signal mixing for modes visualisation based on camera measurement

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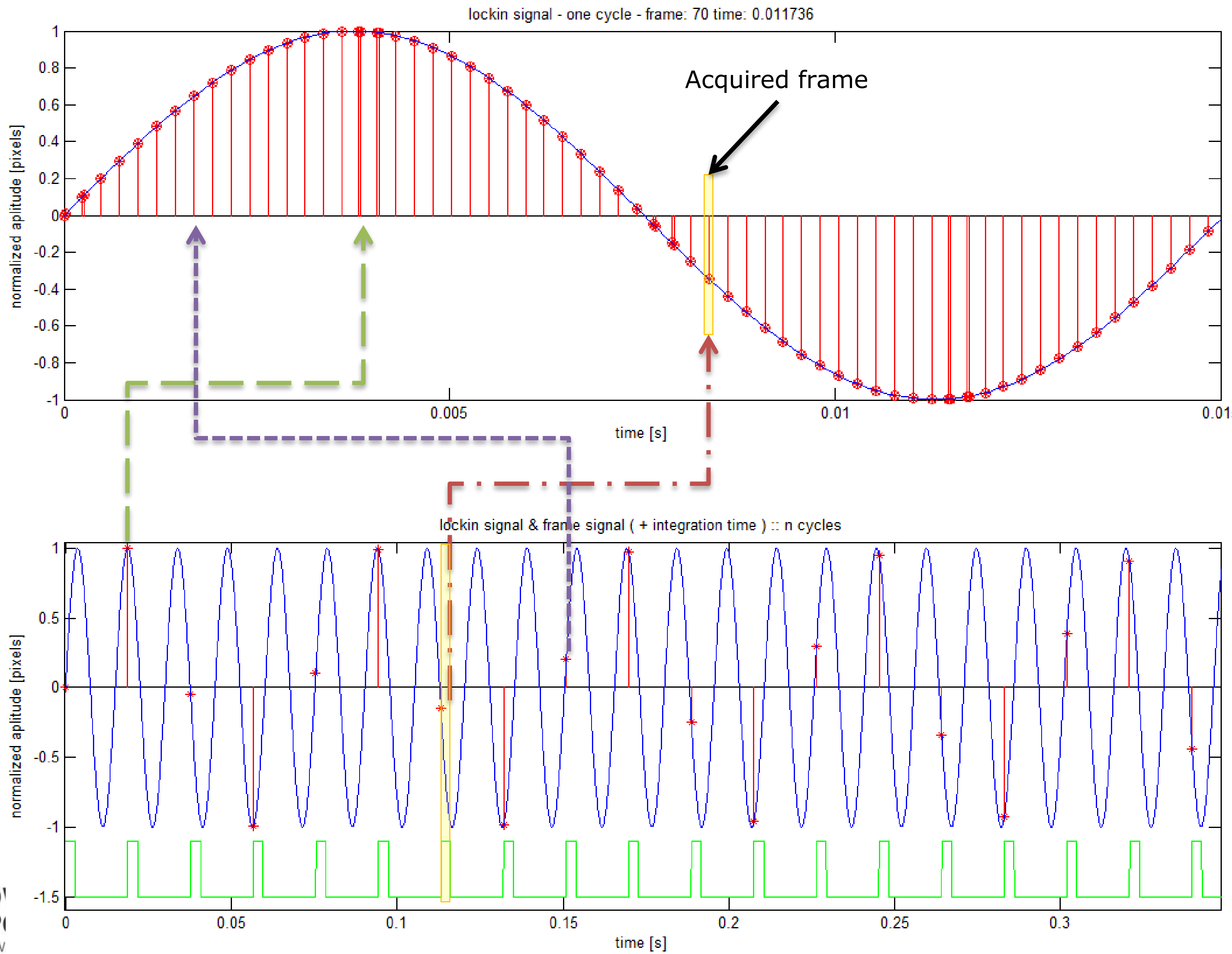
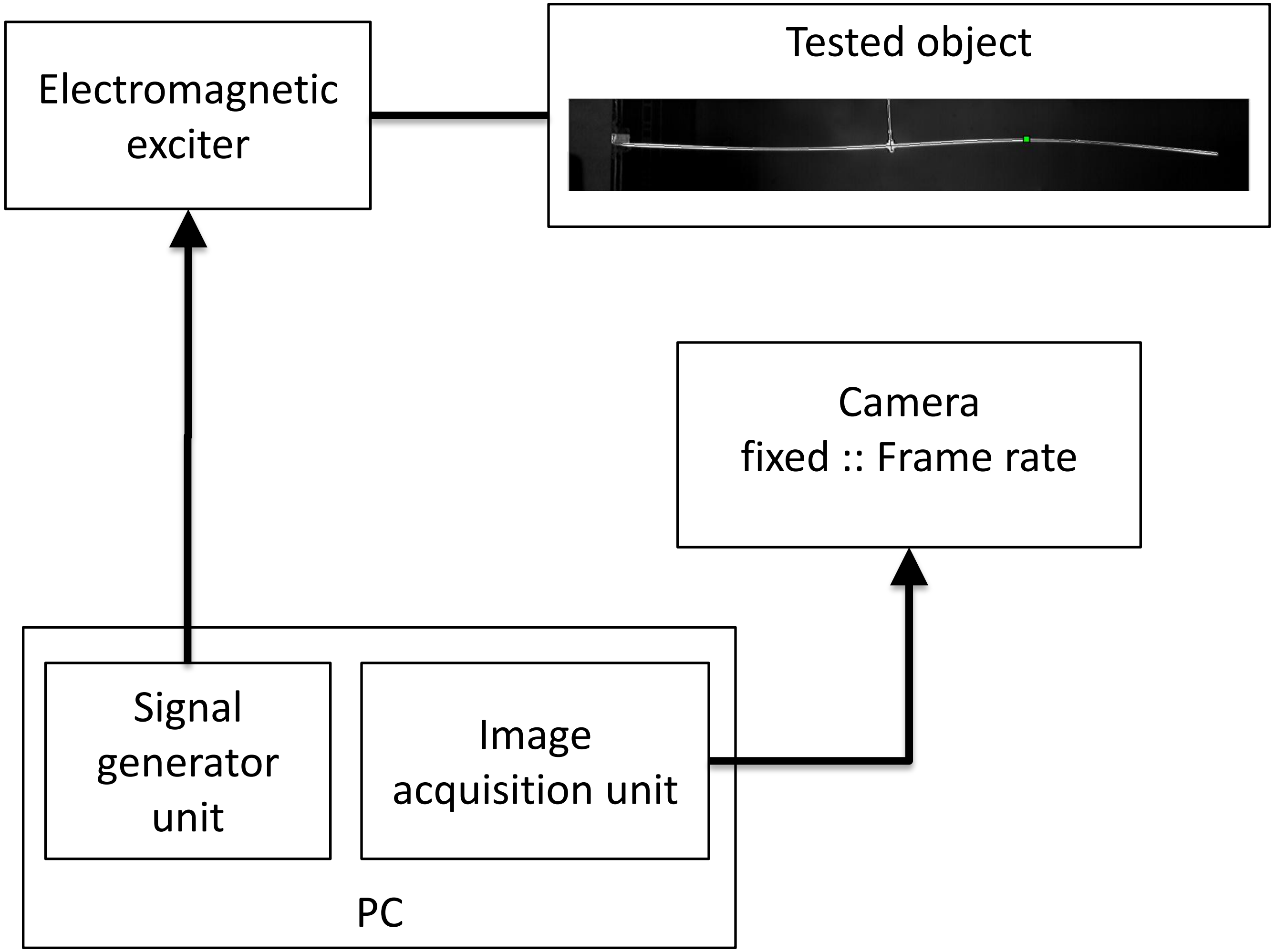
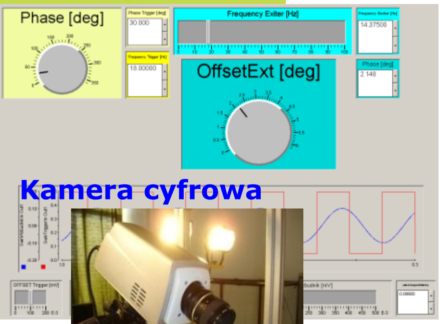

lockin signal - one cycle - frame: 70 time: 0.011736
Acquired frame
normalized aplitude [pixels]
time [s]
0
0.005
0.01
0.015
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
lockin signal & frame signal (+ integration time) :: n cycles
normalized aplitude [pixels]
time [s]
0
0.05
0.1
0.15
0.2
0.25
0.3
1
0.5
0
-0.5
-1
-1.5

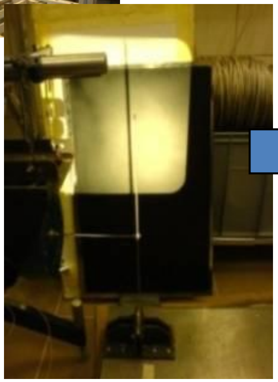
$$resonance\_frequency > camera\_frame\_rate$$



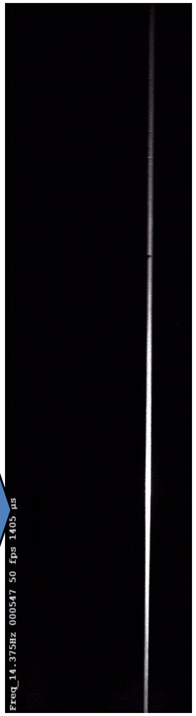
Wizualizacja postaci drgań analizowanych konstrukcji



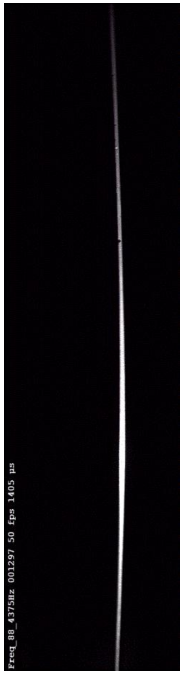
Kamera cyfrowa



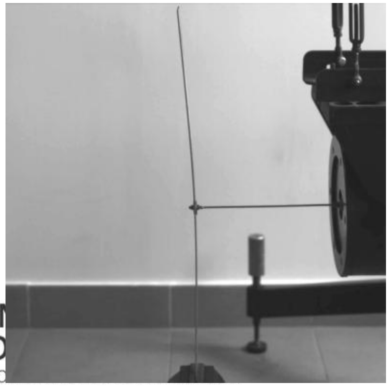
Utwierdzona belka



14.375 Hz



88.4375 Hz

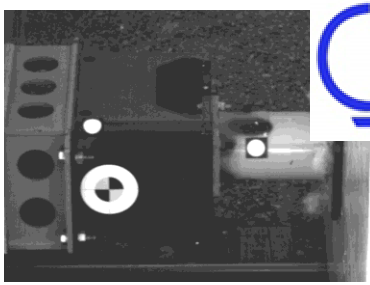


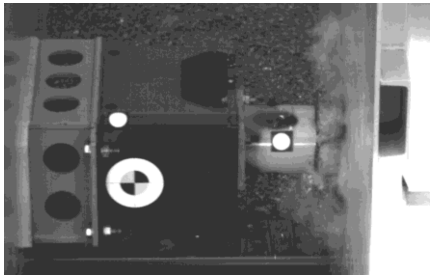
Procesy szybkozmienne

CNTK

Rejestracja pracy absorberów

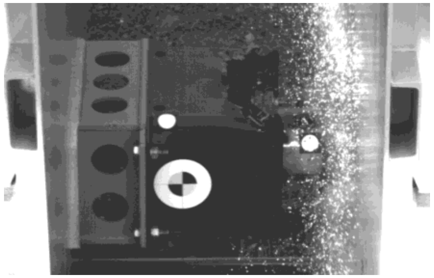
1000 klatek/sek



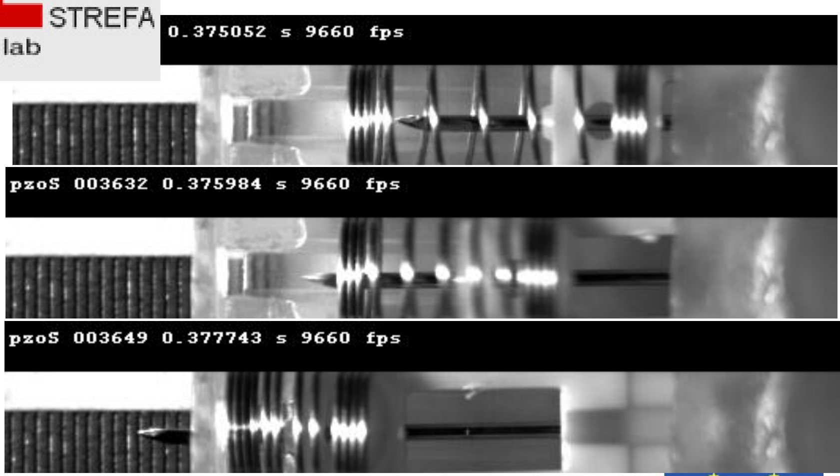


Rejestracja pracy wyrobów medycznych - nakłuwaczy

~10 000 klatek/sek



HTL STREFA high tech lab



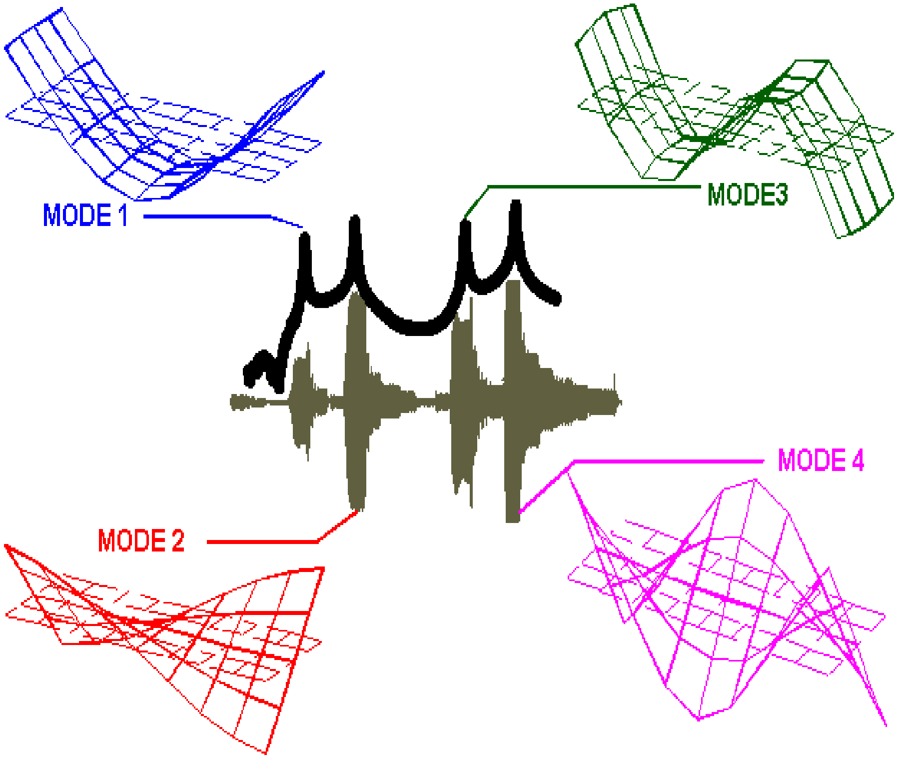
Algorithms – modal filters

The method was introduced in 1982 by Baruh and Meirovitch

The modal filter extracts modal coordinates from measurements of the system response.

It can be applied for:

- ✓dealing with the control spillover problem,
- ✓the vibration control of flexible structures,
- ✓correlation analysis for experimental and analytical modal vectors,
- ✓identification of operational forces from the system response,
- ✓damage detection



Filtering of environmental changes (temperature changes) influence on structural dynamic properties of a structure

Modal filters - reciprocal modal vectors

To construct the discrete modal filter from experimental data, a new type of modal parameters has to be introduced – reciprocal modal vectors ψ_r. They should be orthogonal with respect to the modal vectors, and thanks to that, they are applied to decomposition of the system responses to the modal coordinates η_r.

$$\eta_r(\omega) = \Psi_p{}^T \cdot \{x(\omega)\} = \left(\frac{\{\phi_r\}\{\phi_r\}^T}{j\omega - \lambda_r} + \{\psi_r\}^T \{\phi_r\}^* \frac{\{\phi_r\}^{*T}}{j\omega - \lambda_r{}^*} \right)$$

the assumption that the modal residue R_{rpp} is in the imaginary form:

$$R_{rpp} = j \cdot 1$$

the 1 DOF frequency response function $H_{pp}(\omega)$

$$H_{pp}(\omega) = \frac{R_{rpp}}{j\omega + \lambda_r} + \frac{R_{rpp}{}^*}{j\omega + \lambda_r{}^*}$$

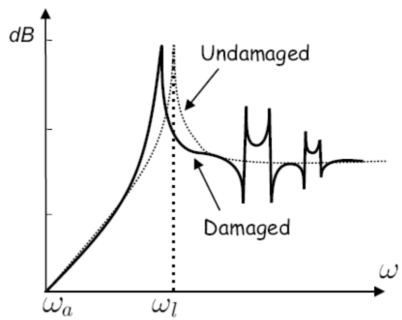
the experimental frequency response functions k x N matrix:

$$H_{kN}(\omega) = \begin{bmatrix} H_1(\omega_1) & H_2(\omega_1) & \cdots & H_N(\omega_1) \\ H_1(\omega_2) & H_2(\omega_2) & \cdots & H_N(\omega_2) \\ \vdots & & & \\ H_1(\omega_k) & H_2(\omega_k) & \cdots & H_N(\omega_k) \end{bmatrix}$$

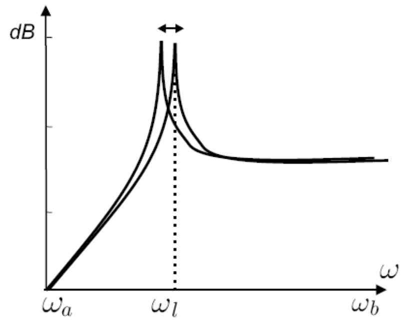
reciprocal modal vectors matrix Ψ_p determination:

$$\Psi_p = H_{kN}{}^+ \cdot H_{pp}$$

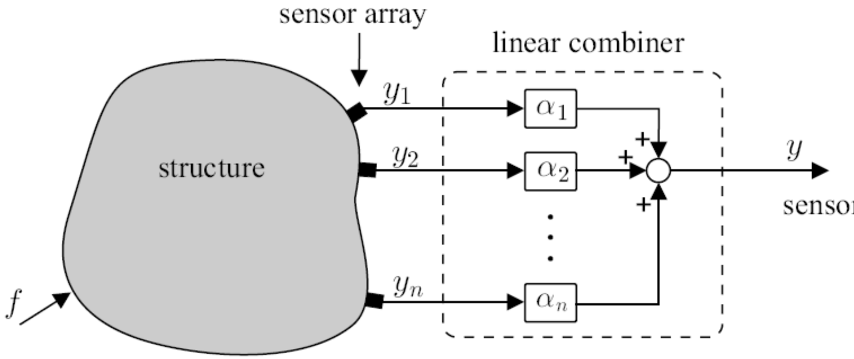
Algorithms – modal filters



Damage



Environmental change



Local change of stiffness

$$M^{-1}\cdot(-K_u)\cdot\Phi=\Phi\cdot\Lambda$$

$K_d = K_u \pm \Delta K$ $K_t = \alpha \cdot K_u$

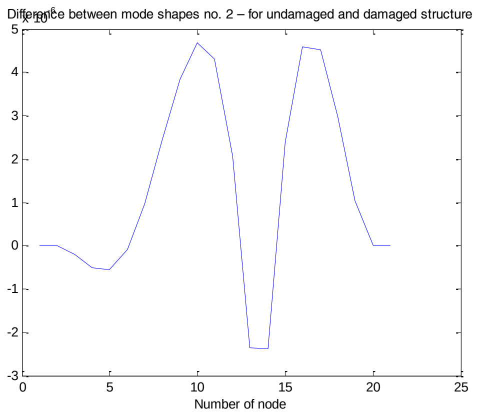
$$M^{-1}\cdot(-\alpha\cdot K_u)\cdot\Phi_t=\Phi_t\cdot\Lambda_t$$

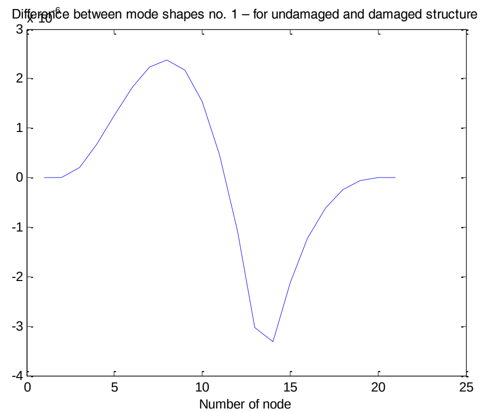
$\Lambda_t = \alpha \cdot \Lambda$ and $\Phi_t = \Phi$

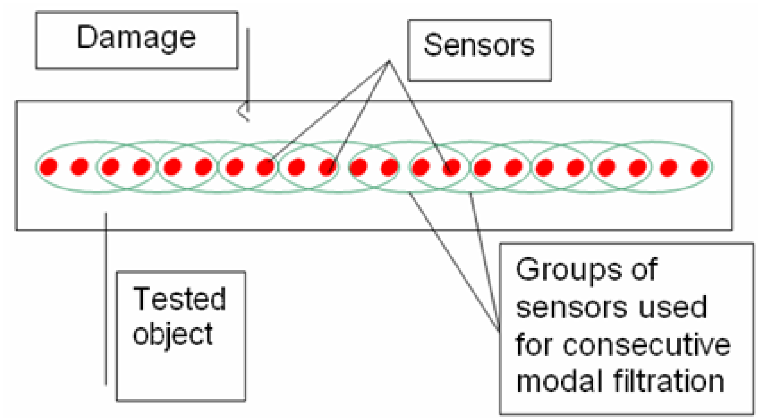
Conclusion: any method based on the modal vectors is resistant for environmental changes

Algorithms – modal filters – damage localization

Differences between mode shapes of damaged and undamaged beam with 10 % crack





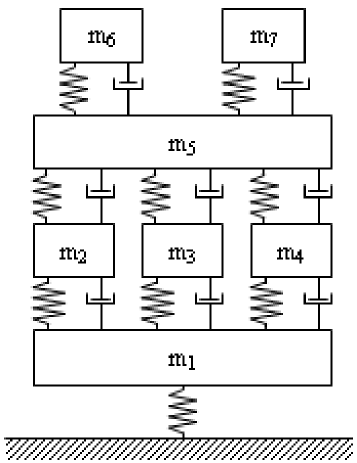


$$DI_4 = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega}$$

Procedure

- Preliminary calculations performed for an object in the reference (undamaged) state – modal analysis, calculation of Reciprocal Modal Vectors for all sensors and for sensors from consecutive areas.
- Measurements of object characteristics in their current state and their filtration with the use of a "global" modal filter.
- In the case of damage detection in Point 2 of the procedure, filtration of groups of characteristics from consecutive object areas with the use of "local" modal filters.
- Calculation of the damage index DI for each of the sensor regions.

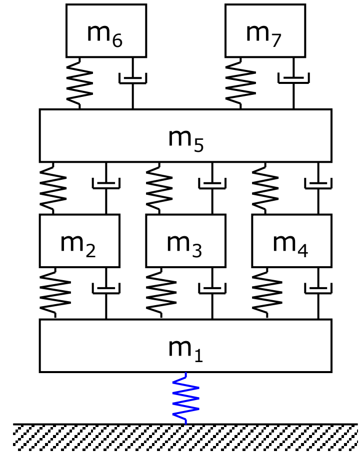
Numerical verification - model



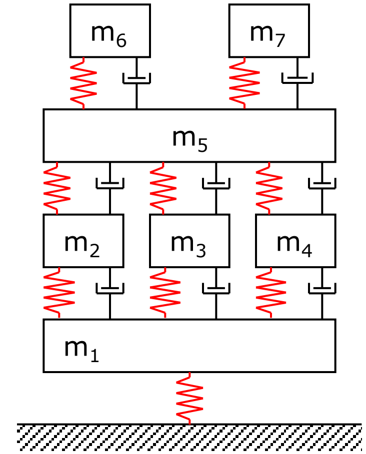
Modal model (natural frequencies, modal damping coeff., modal vectors)

Modal filter (reciprocal modal vectors)

Damage
5% stiffness drop in spring no. 1



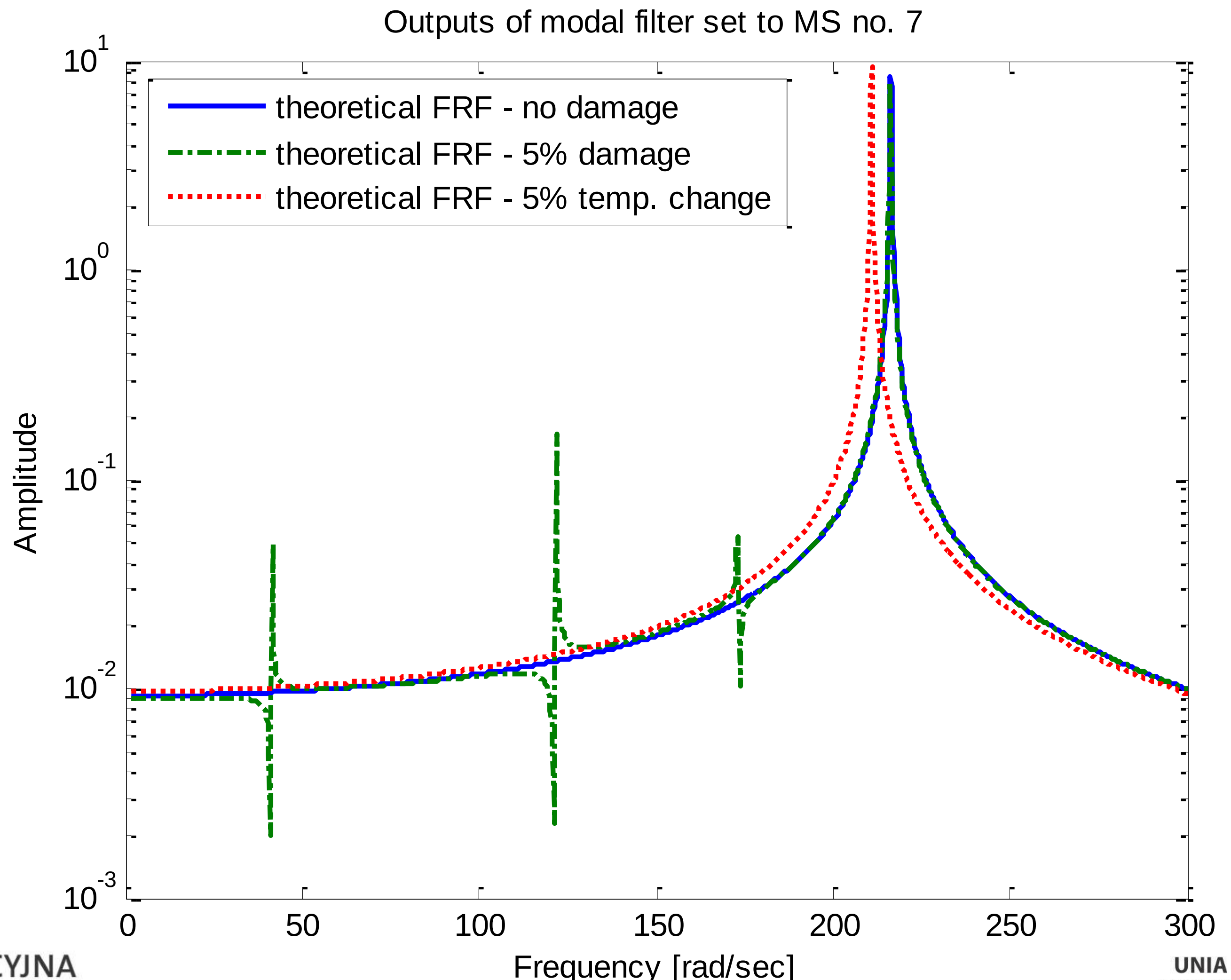
Temperature change
5% stiffness drop in all springs



FRF synthesis

Modal filtering

Numerical verification - results



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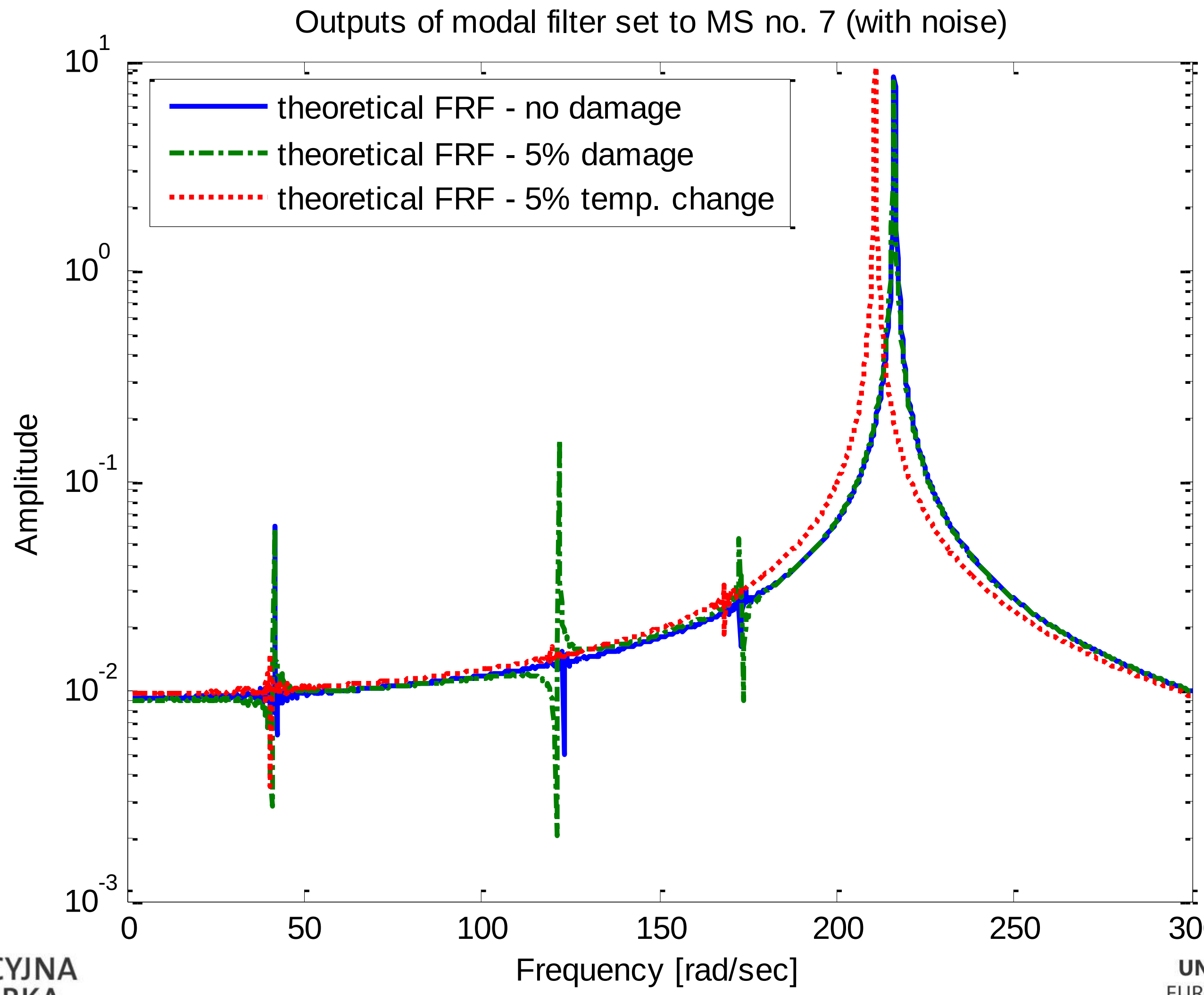
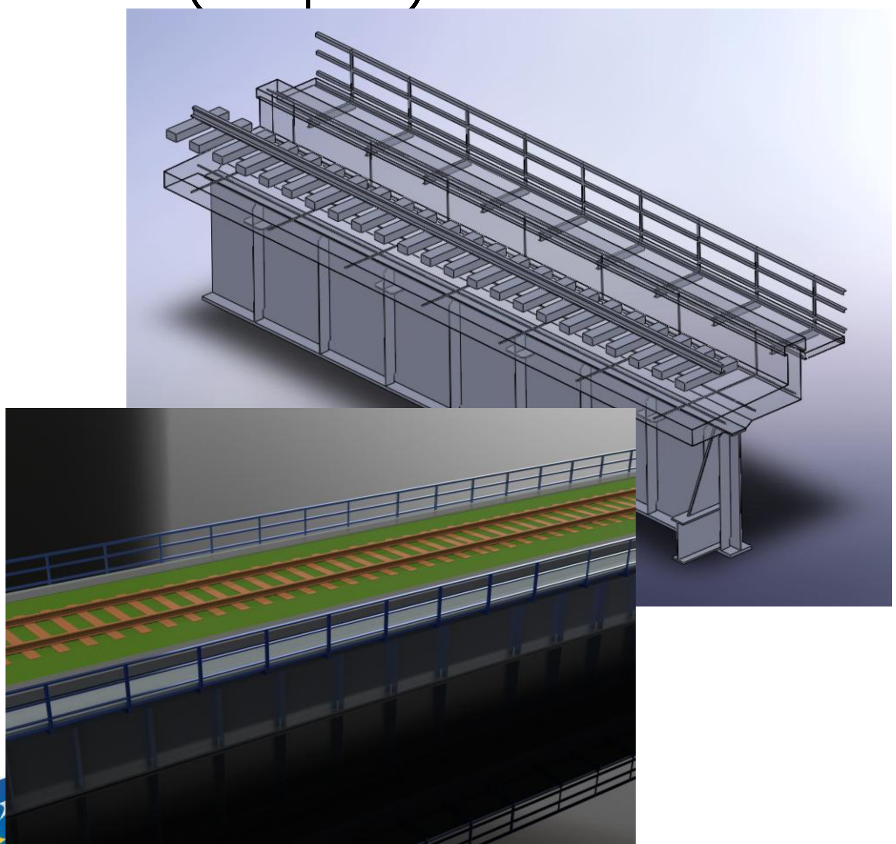
Numerical verification - results

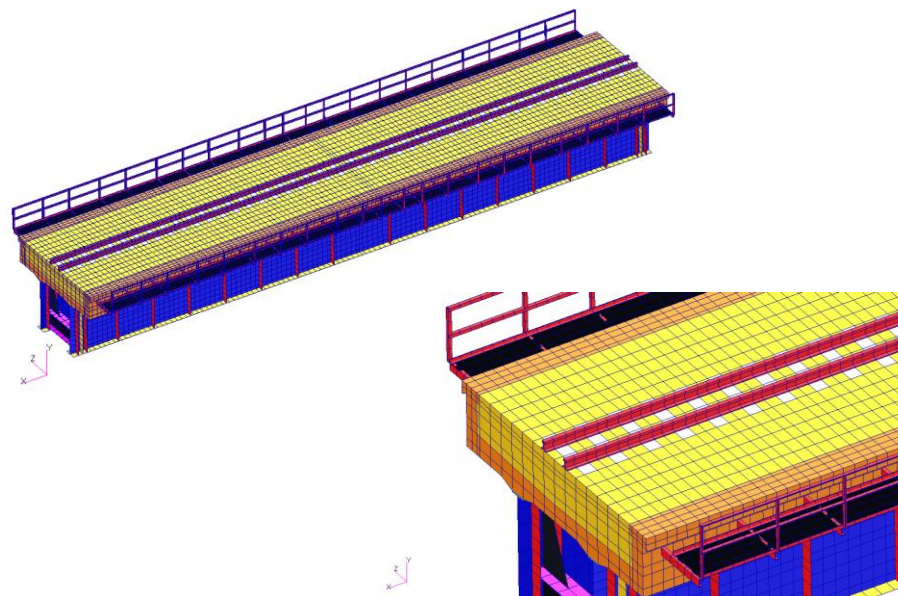


Model of the rail viaduct

CAD model was based on documentation of real structure. Bridge is 27 m long and consists of steel (beams, barriers, rails, reinforcement of main plate), concrete (main plate, pavements), soil (sub-crust) and wood (sleepers) elements.



FEM model was built. Is consists of approximately 28500 elements and 30500 nodes. Solid, shell and beam elements were used in the model



Model of the rail viaduct

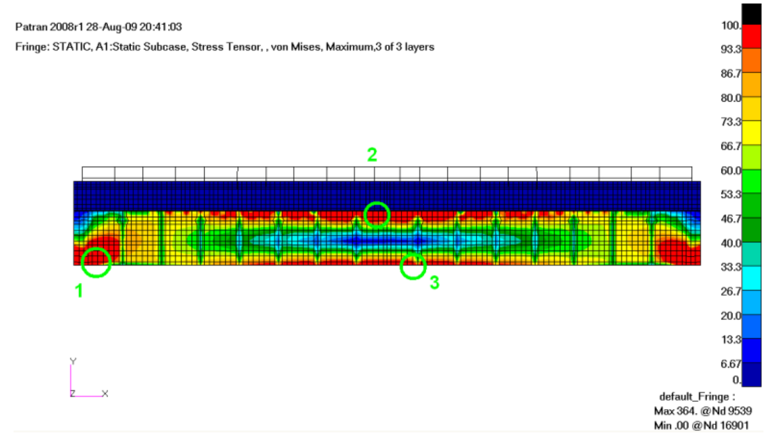
There were three cracks introduced in the model. First and second are vertical cracks in web, third is flange crack. Crack localization was based on linear-static stress analysis.

	Steel (20°C)	Wood	Concrete	Soil
E	$2.1 \cdot 10^{5}\ MPa$	$0.11 \cdot 10^{5}\ MPa$	$32.4 \cdot 10^{-3}\ MPa$	$10\ MPa$
υ	0.3	0.06	0.167	0.15
ρ	$7.85\ \frac{g}{cm^3}$	$0.8\ \frac{g}{cm^3}$	$2\ \frac{g}{cm^3}$	$2\ \frac{g}{cm^3}$

To take into account influence of moisture, different material densities were used

Moisture (W)	Density
15 %	$0.92\ \frac{g}{cm^3}$
25 %	$1\ \frac{g}{cm^3}$

Moisture (W)	Density
5 %	$2.1\ \frac{g}{cm^3}$
8 %	$2.16\ \frac{g}{cm^3}$



The following normal modes analysis scenarios were considered:

Without crack (dry)

Without crack (moist)

Without crack (wet)

Crack 1

Crack 2

Crack 3

Crack 123

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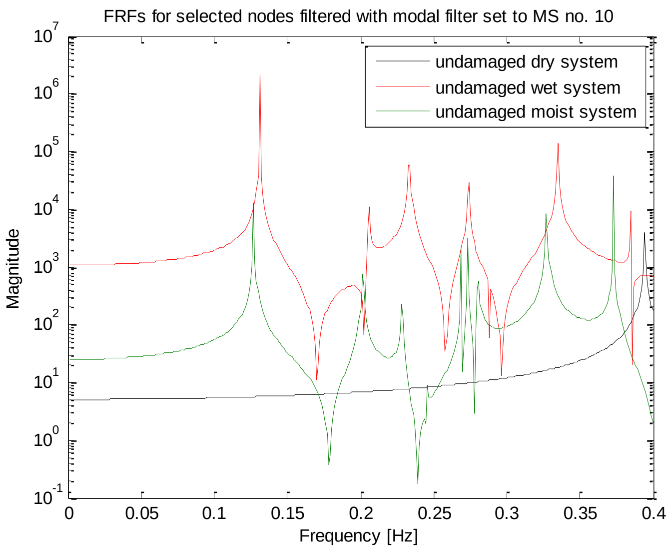
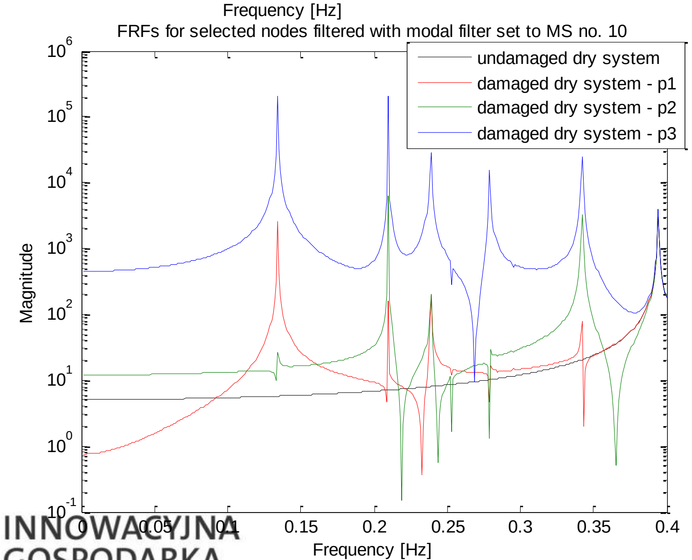
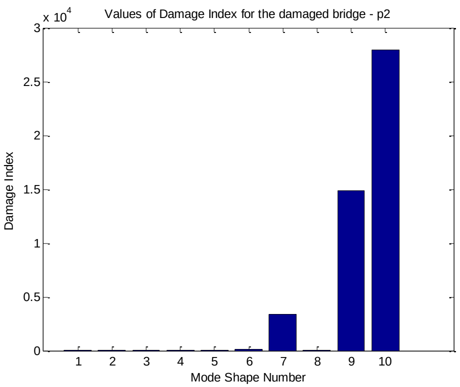
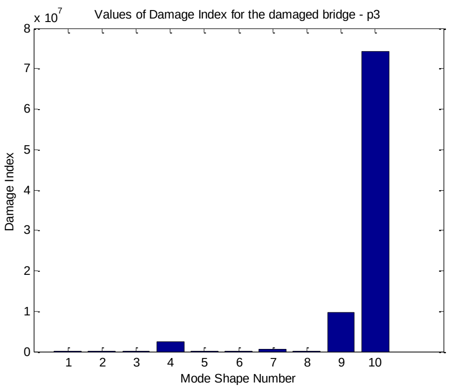
Humidity - results

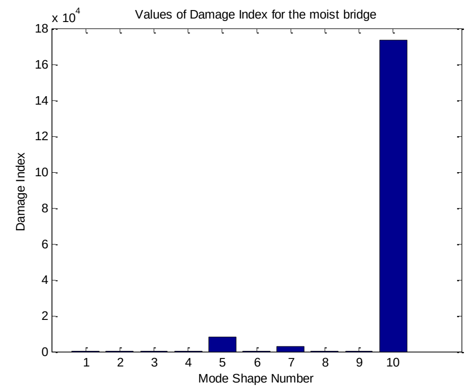


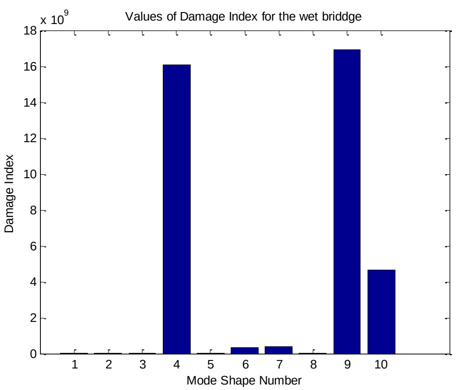


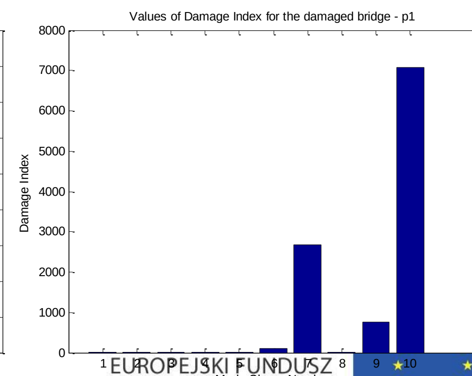
$$DI_4 = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega}$$







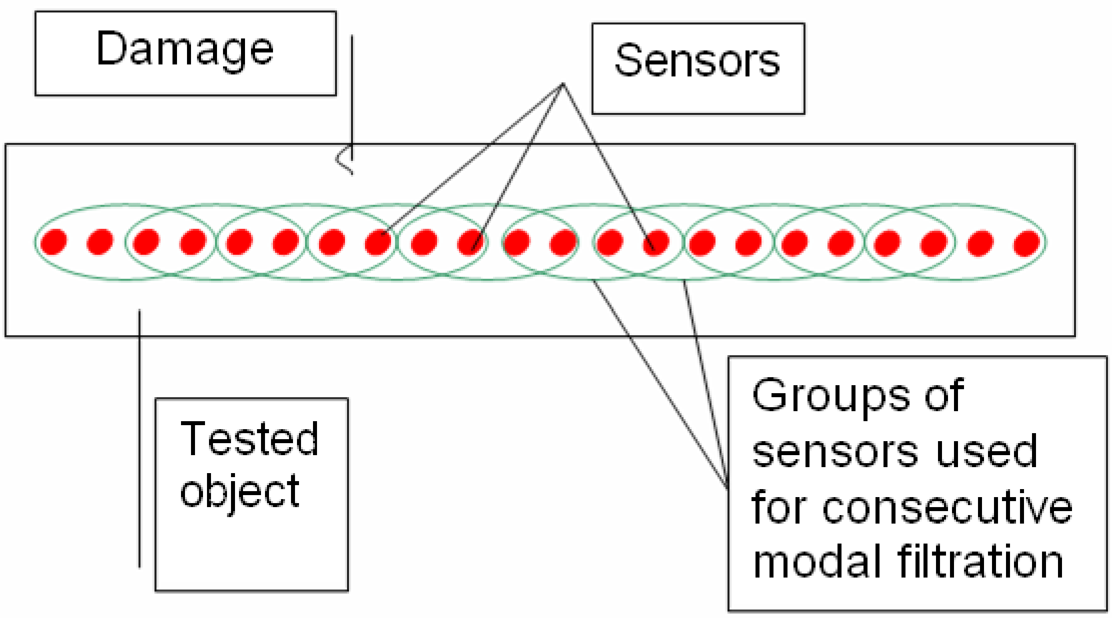




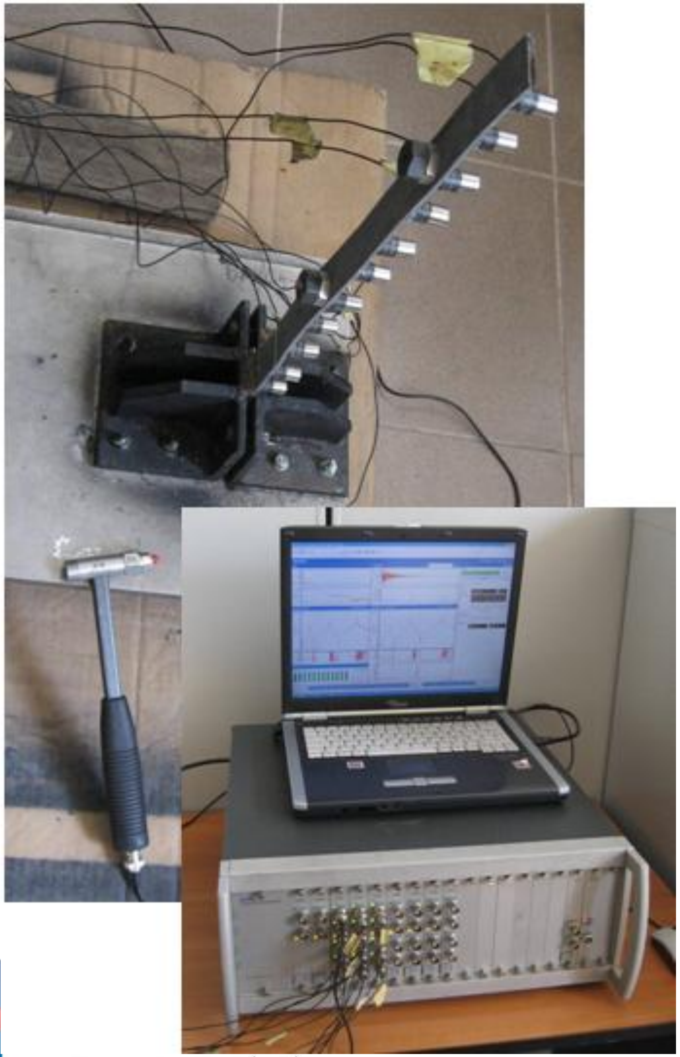
Damage localization

The idea for extension of the method by adding damage localization, bases on two facts:

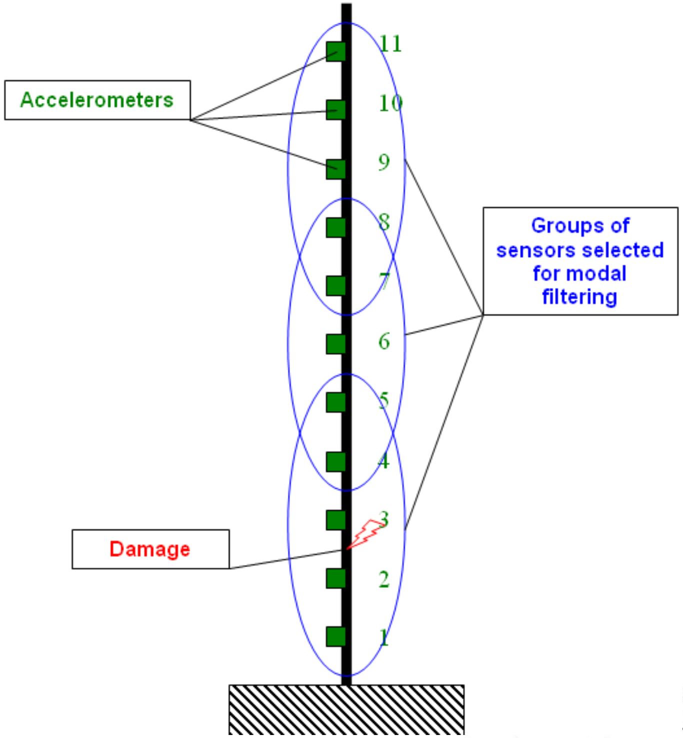
1. Effective modal filter can be formed for just a few sensors (in practice about 4 - 5),
2. That damage, in most of the cases, disturbs the mode shapes (modal vectors) only locally.



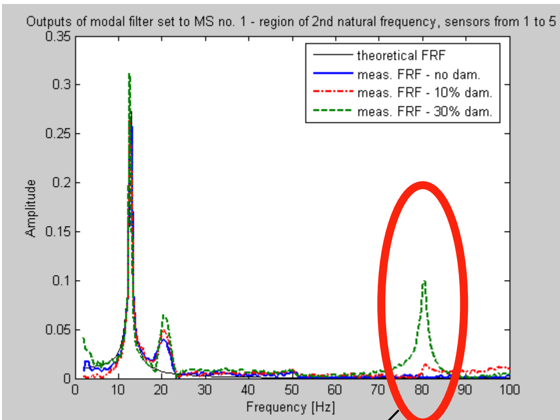
Experimental verification – laboratory stand

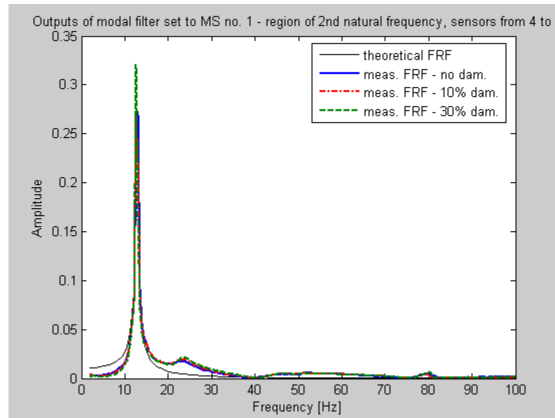


Three modal tests were performed, first on the undamaged beam. Next the cut between measuring points 2 and 3 was introduced. The magnitude of the cut amounted consecutively 10 % and 30 % of the beam cross-section area.



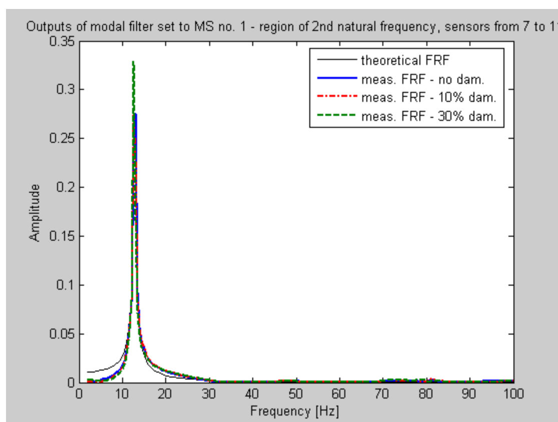
Experimental verification– results

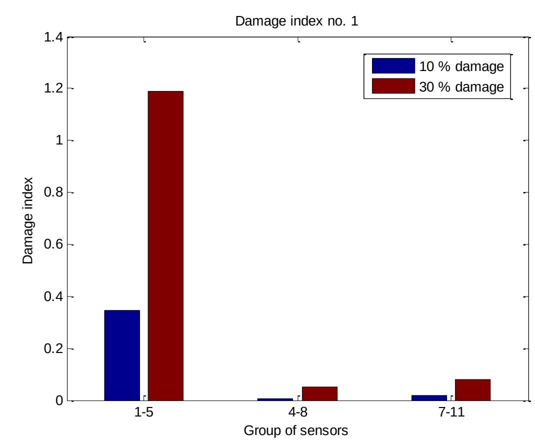


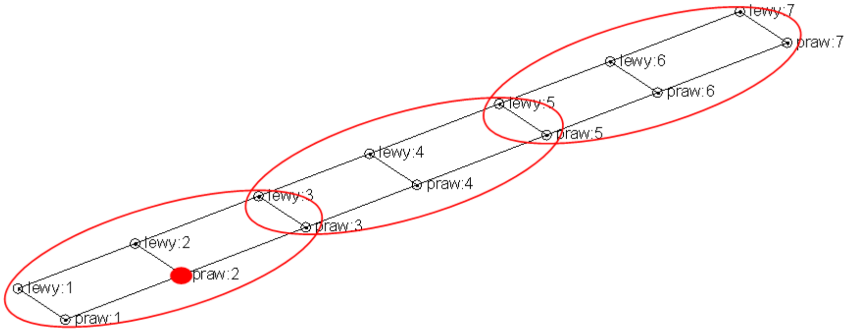


$$DI_4 = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega}$$

damage location



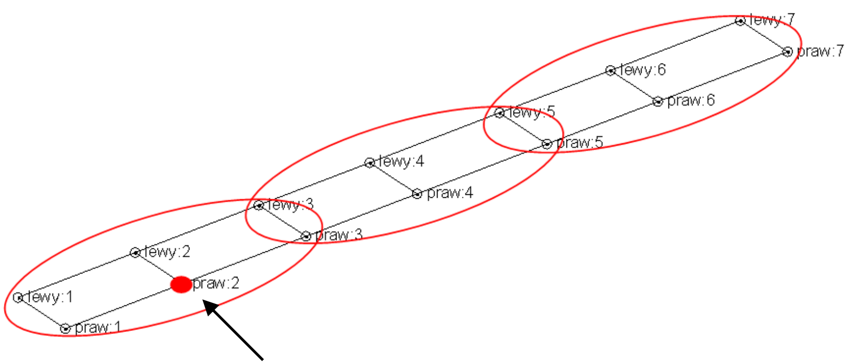




Experimental modal analysis with impact excitation

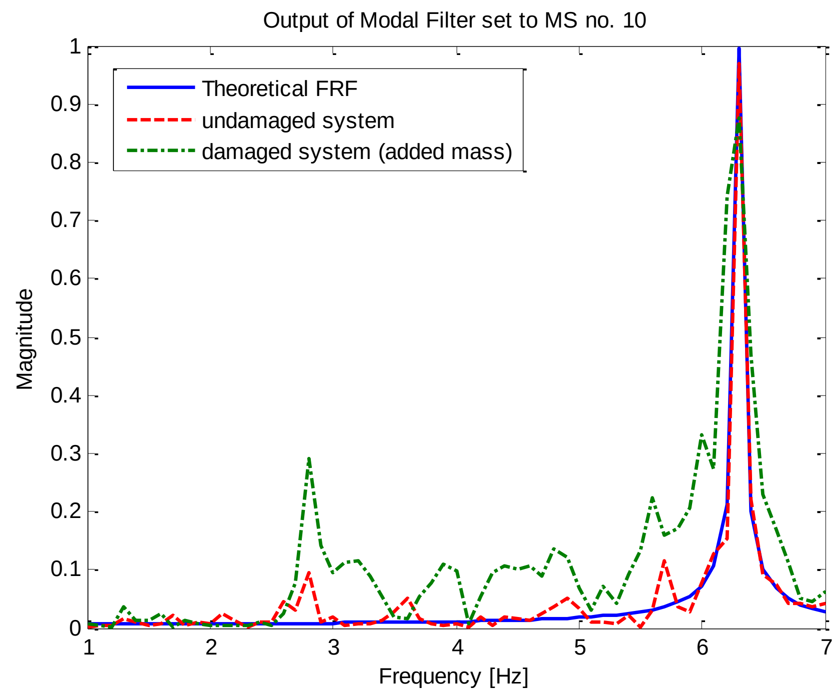
Nr CzDW	CzDW [Hz]	WTM [%]
1	1.35	0.36
2	1.59	1.29
3	2.06	0.13
4	2.82	0.50
5	3.01	1.77
6	3.66	0.03
7	4.99	1.22
8	5.15	1.26
9	5.62	1.02
10	6.29	0.33

Case studies – modal filter for footbridge

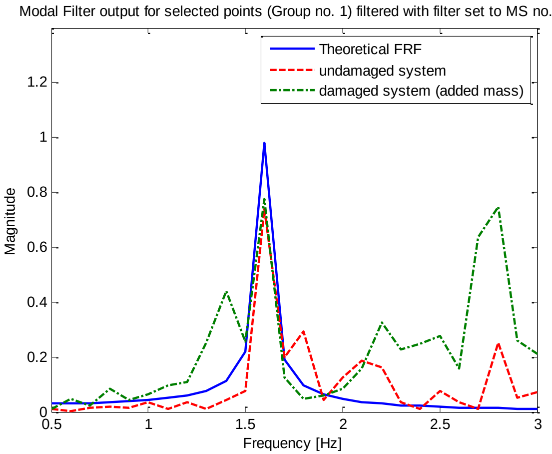


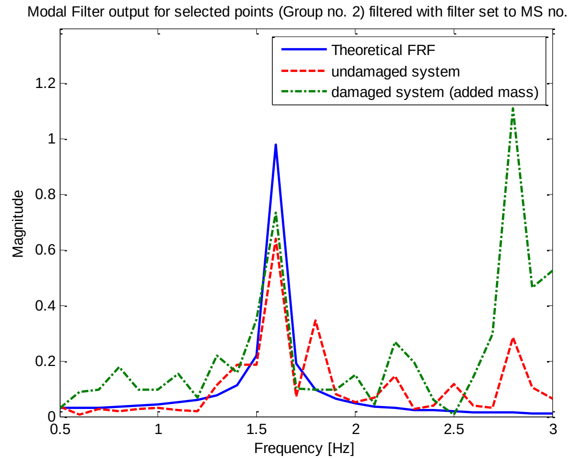
Added mass - about 200 kg

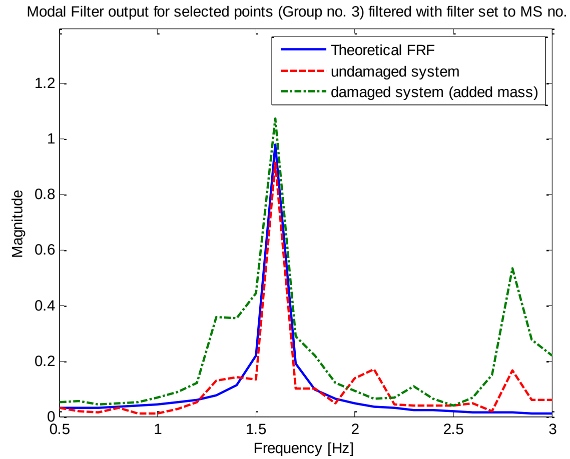
Ambient excitation

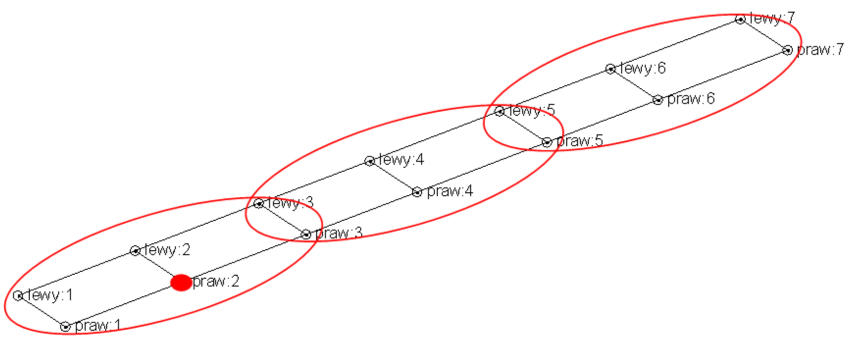


Case studies – modal filter for footbridge

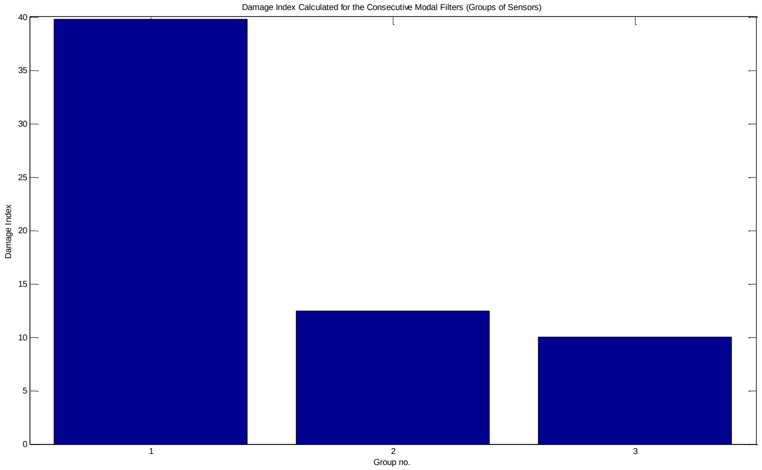








Added mass - about 200 kg



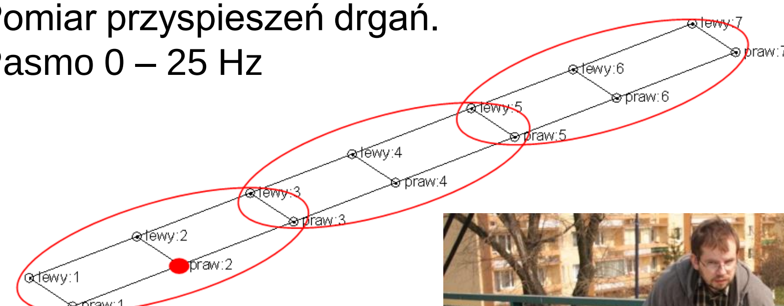
Badania kładki dla pieszych nad ulicą Opolską dla Zarządu Infrastruktury Komunalnej i Transportu w Krakowie

Obiekt badań: kładka dla pieszych nad ulicą Opolską.

Rodzaj kładki: podwieszona, dla pieszych;
Ilość przęseł: 2 podwieszone + część podparta;
Rozpiętość: 39,00 m + 39,00 m + 42,00 m;
Pylon: stalowy, typu A; Wysokość pylonu: 34,52 m;
Układ nośny: układ podwieszony, promienisty, zbieżny;

Przeprowadzono dwa testy modalne,

Wymuszenie impulsowe
Sieć 14 punktów pomiarowych
Pomiar przyspieszeń drgań.
Pasmo 0 – 25 Hz



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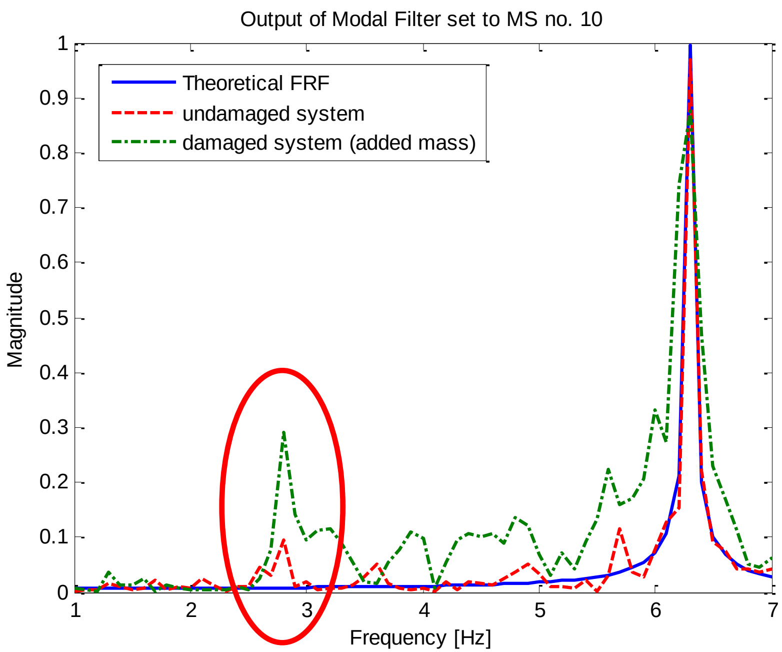
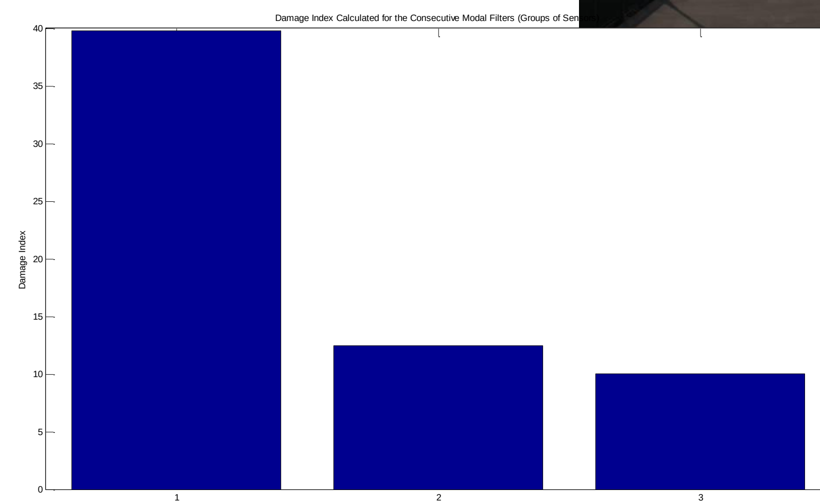
Badania kładki dla pieszych nad ulicą Opolską dla Zarządu Infrastruktury Komunalnej i Transportu w Krakowie



Uszkodzenie symulowane było poprzez dodanie masy około 200 kg zlokalizowanej w punkcie pomiarowym Praw:2. (około 5% masy obiektu w najbliższym otoczeniu).



Zasymulowane uszkodzenie zostało poprawnie wykryte i zlokalizowane

Rejon uszkodzenia

Conclusions

- SHM systems improve safety of operation of critical structures
- Long term monitoring is required
- Local methods are more sensitive then global one
- SHM system are expensive (local system)
- Detection and localization, assessment are relatively easy
- Prediction is very difficult task
- Interdisciplinary approach is required
- SHM systems commercial use in civil structures, aviation, space, railway,power plants.

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