MATLAB EXPO 2018

The European Commission's science and knowledge service

Joint Research Centre

Directorate E
Space, Security and Migration

Unit E.4
Safety and Security of Buildings

A MATLAB Toolbox for Experimental Modal Analysis of Structures

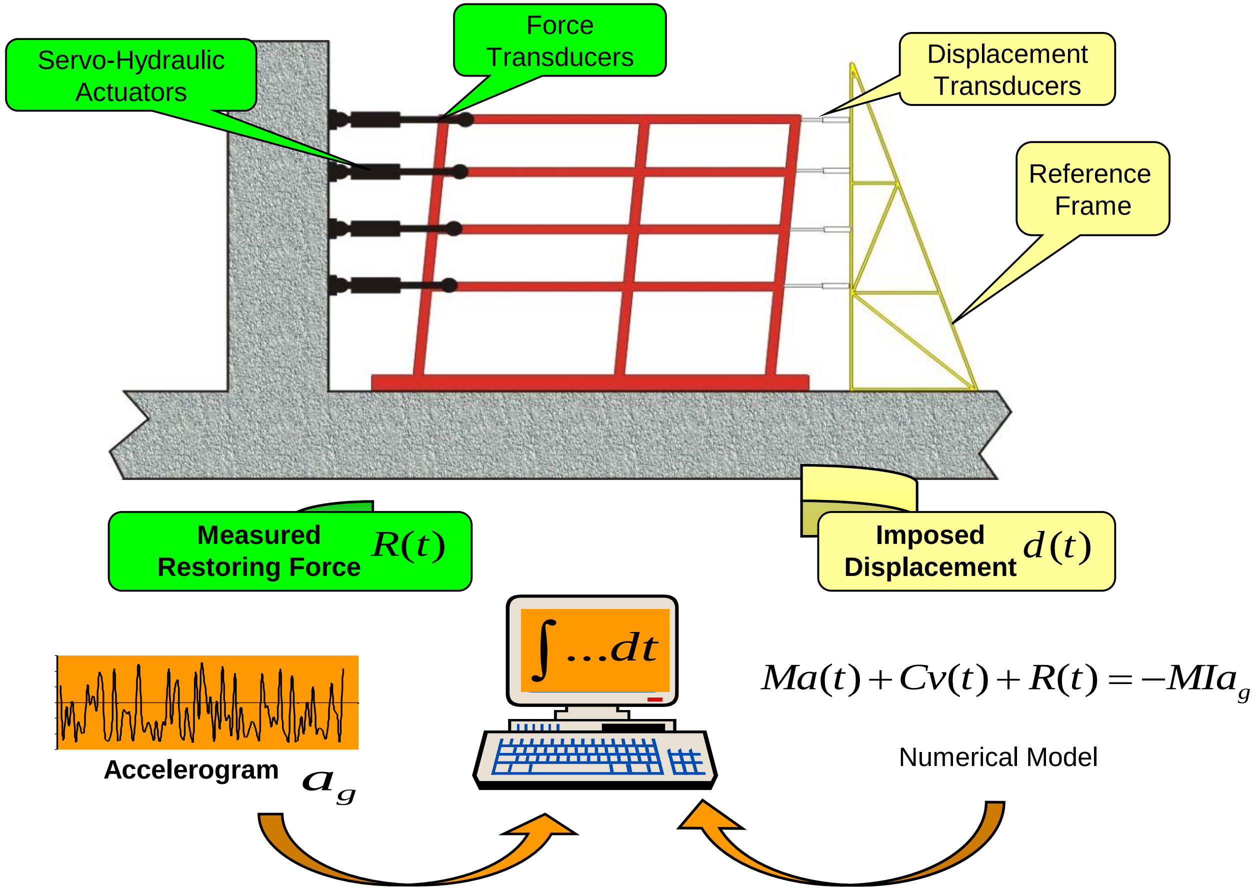
Daniel Tirelli
daniel.tirelli@ec.europa.eu

29 Maggio 2018
Milano

European Commission

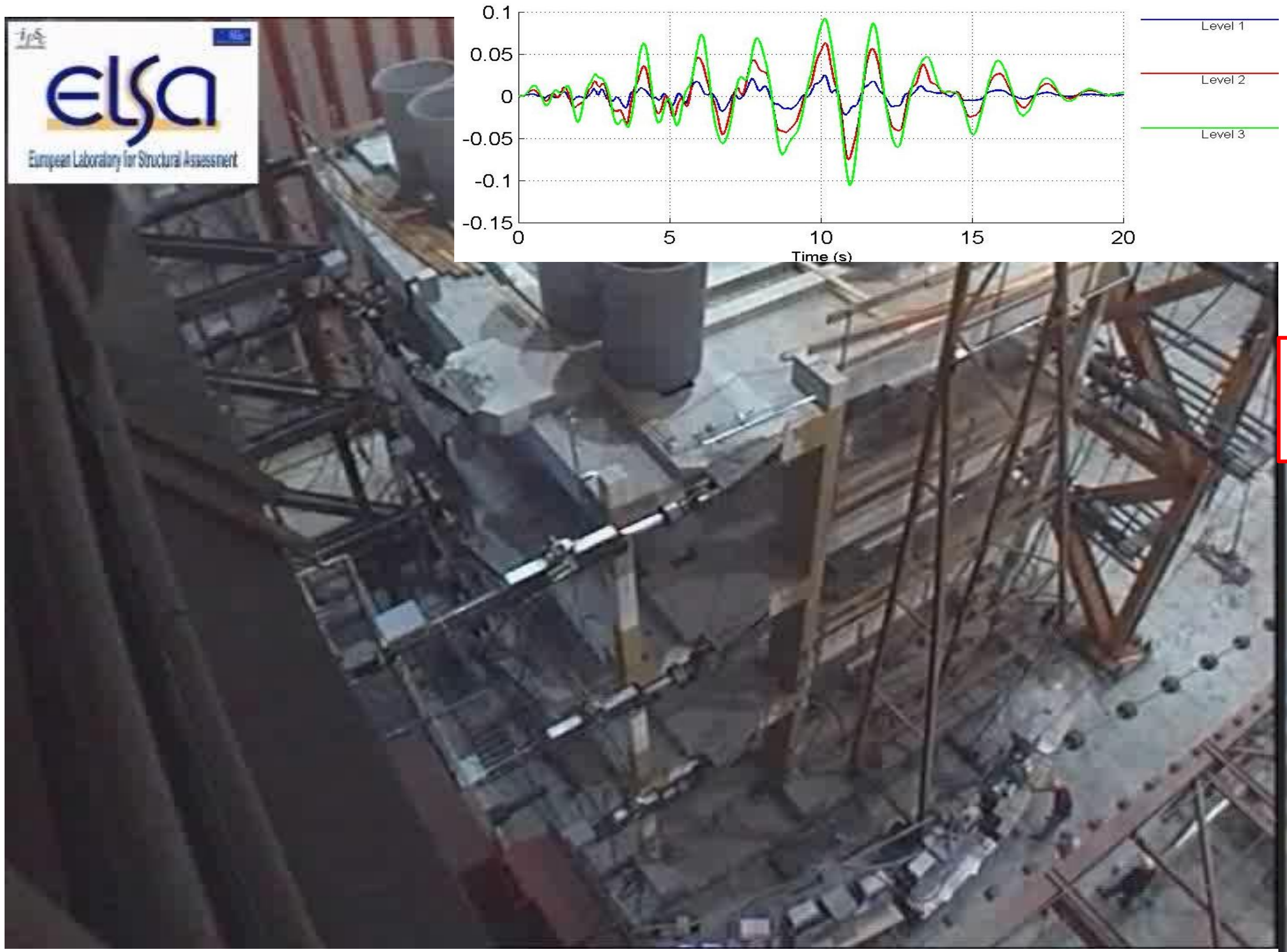
ELSA Laboratory: The European Laboratory for Structural Assessment

Activity mainly for European Standards in Civil Engineering



The Pseudo Dynamic Method

Example of bi-directional test at real scale



Resonances

Dynamic Inputs

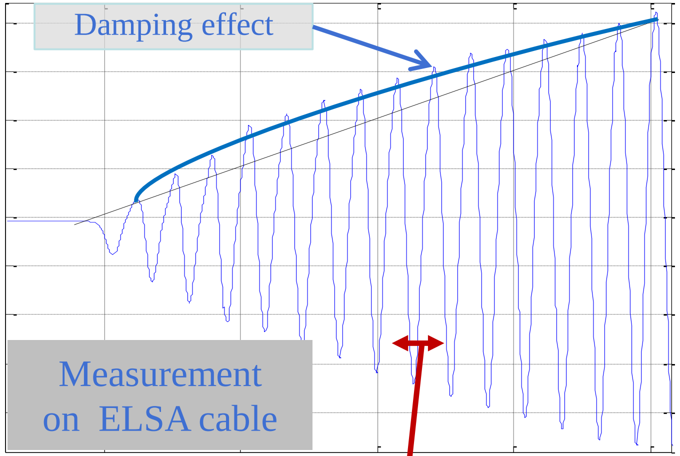
Seism Wind Rain Traffic

For flexible structures, ex: Bridges, Cables etc… Sometime resonances are visible to the naked eye.

Storm on Volgograd Bridge (Russia 2010). Source: *YouTube*

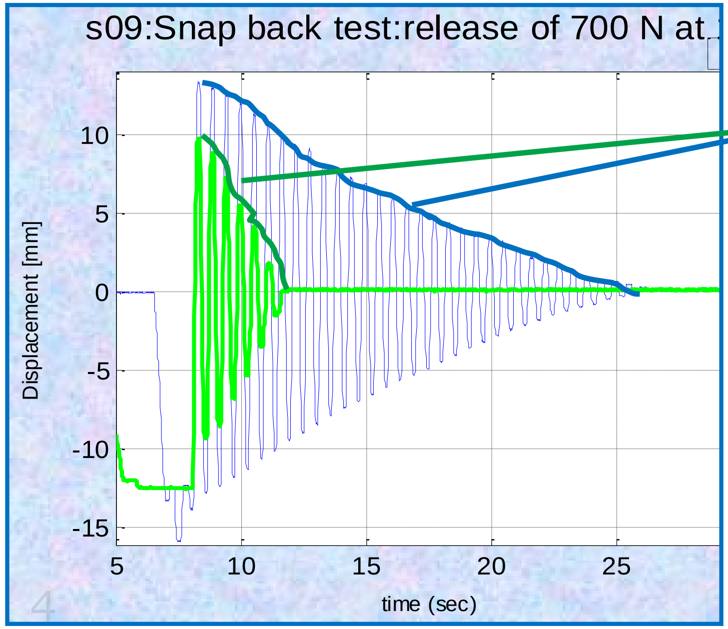
What to understand from resonances?

Dangerous for structures

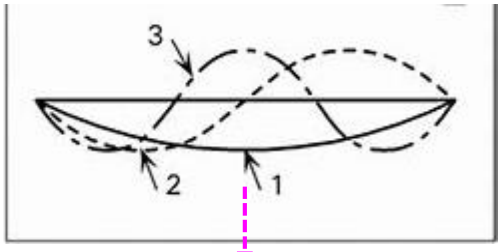


Frequency

Mode Shapes φ_i Amplitude at different positions



Damping ζ



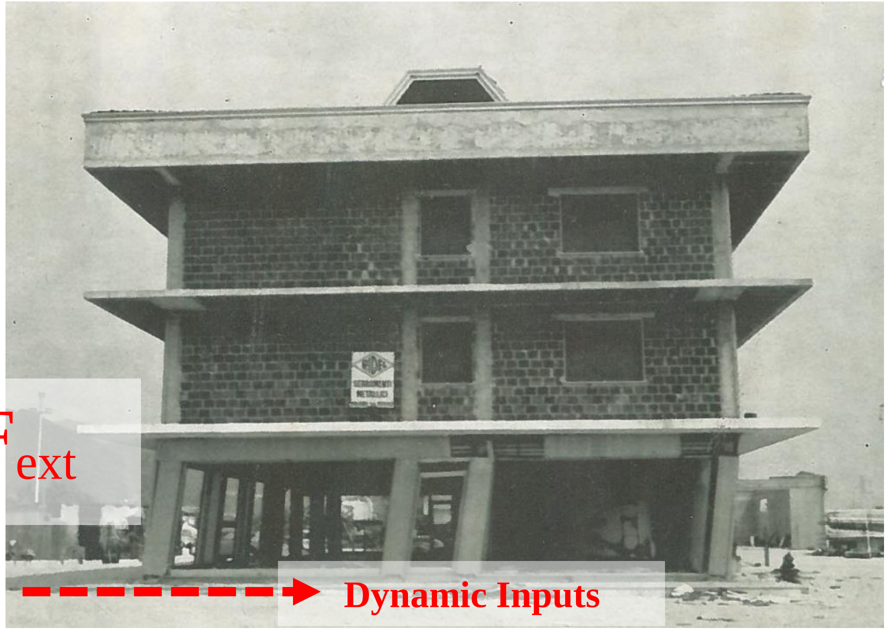
From measurements at different positions of the structure the toolbox calculates the three parameters which govern resonances

They depend from the structure only (not from the input).

Equation of motion of the structure

Inertial Forces | Damping Forces | Reaction Forces

$$[M]\{x''\} + [2.\zeta.\omega]\{x'\} + [K]\{x\} = F_{ext}$$



Source: Messaggero Veneto. Friuli Earthquake 1976

Damping

Frequency~ $(K_i/M_i)^{1/2}$

Mode Shapes φ_i
Amplitude at different positions j

J positions

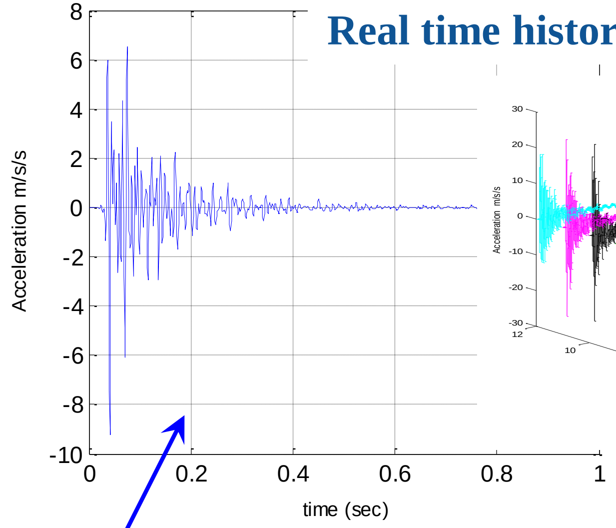
The three parameters calculated by the toolbox from experiments

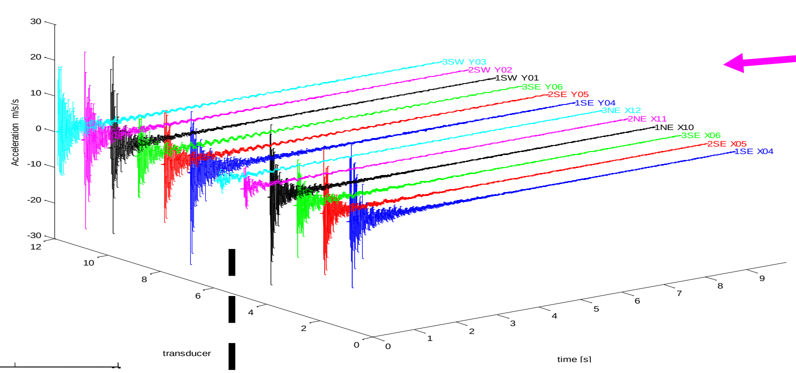
Could give:

- *The mechanical state of the structure (damaged or not)*
- *Reference values to implement numerical models*

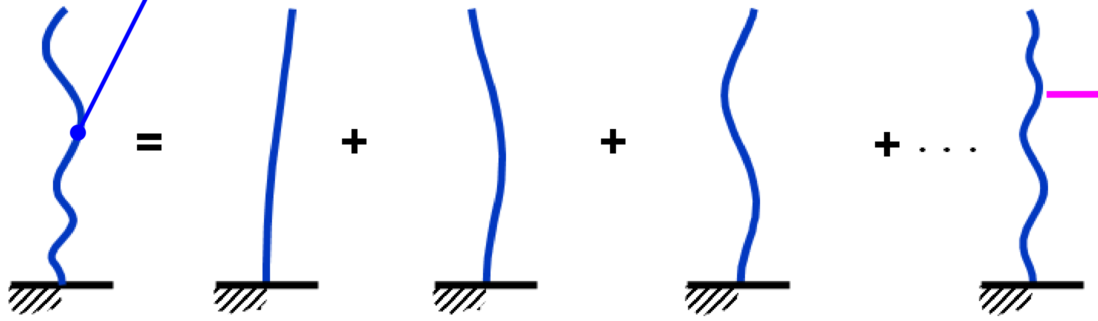
Practically

Real time history signals from a dynamic event





Fourier Transform



Physical Domain

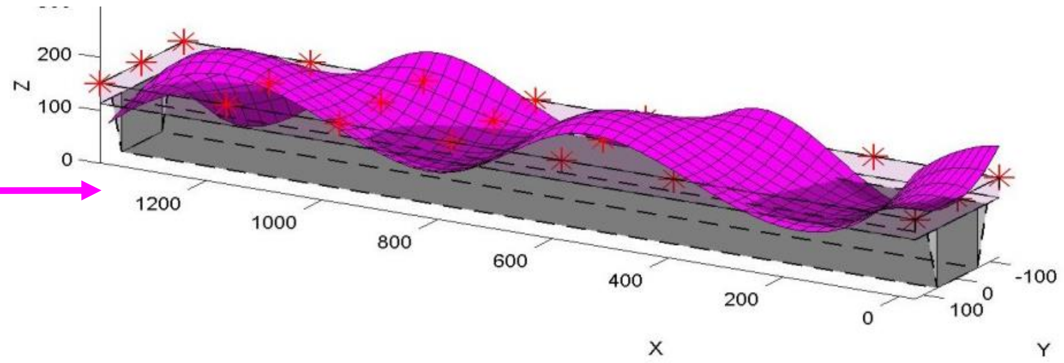
Mode 1: f_1, ζ_1, Φ_1

Mode 2: f_2, ζ_2, Φ_2

Mode 3: f_3, ζ_3, Φ_3

Mode *n*: f_n, ζ_n, Φ_n

The "Genome" of the structural motion



Aim of the Experimental Modal Analysis Toolbox: extract parameters from "complex" signals

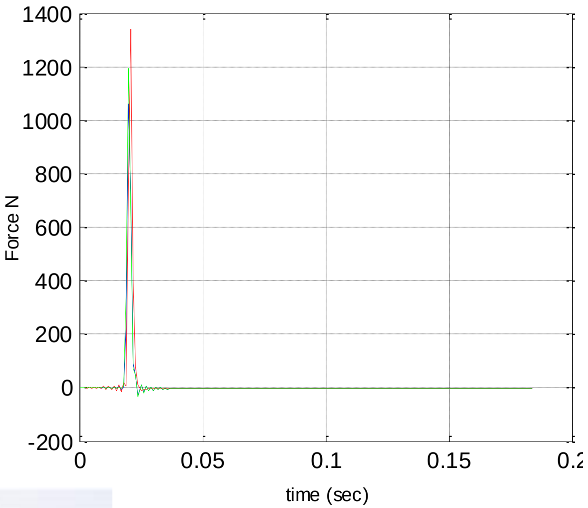
European Commission

Instrumentation

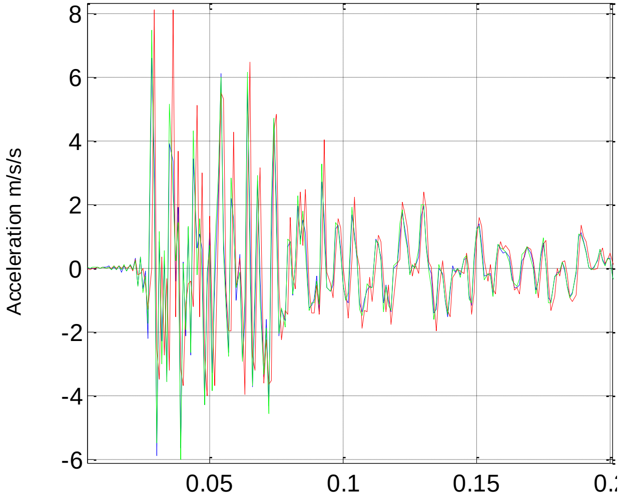
(Input)

Hammer Impact

Input signals X(t) in position i

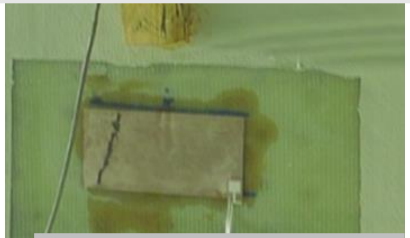


Output signals Y(t) in position j



(Output)

Accelerometer



Piezo-Patch (Embedded sensor)

Truck Impact

Displacement transducers

Wireless Acc.

The toolbox is divided in two parts: in each of them MATLAB eases and shortens the signal processing

- methods
  - Slide 9
- controls
  - Slide …
- interpolations
  - Slide 13

1

Process the data during the acquisition

- Extraction
  - Slide 14
- Mode shapes
  - Slide …
- Videos
  - Slide 20

2

After the acquisition extracts the experimental modal parameters displaying results in different forms

Acquisition Methods

The toolbox runs with two types of tests

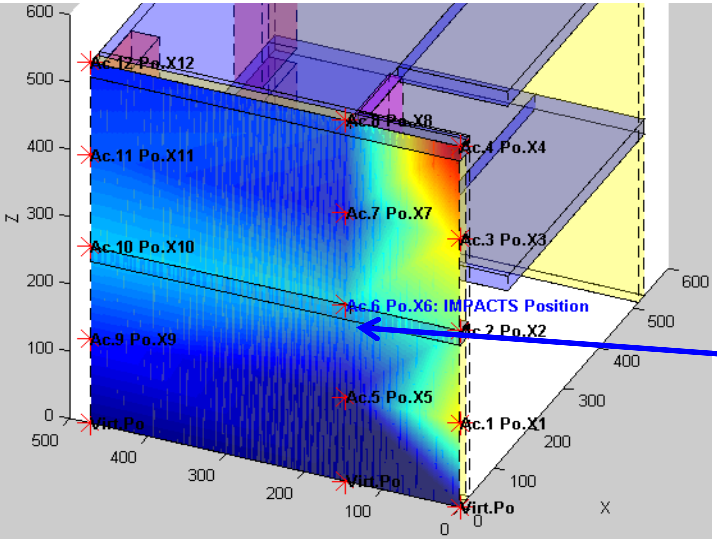
Fast Impact Hammer Test (FIHT)

Possible only with a fast check of the coherence function (values near 1)

MATLAB 1

j limited by the number of Output transducers

j is not limited ! More experimental data more accurate results. It is possible to test additional positions etc…



j Accelerometer positions

Ref.

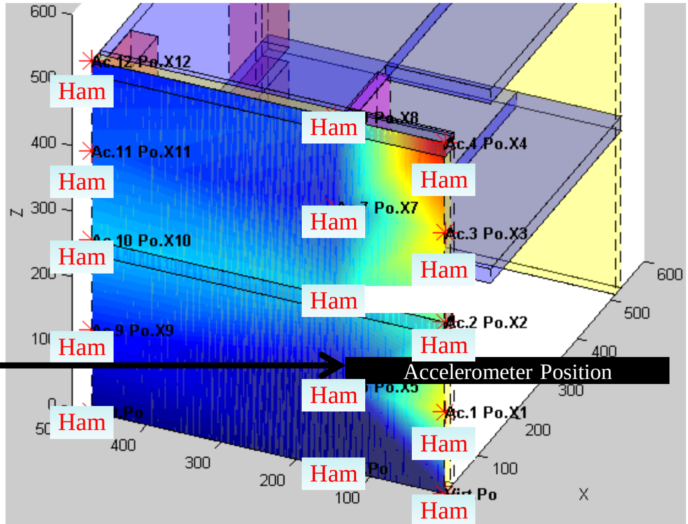
Use of reciprocity property of the FRF (Transfer Function)

$$H_{ij}(\omega_k) = H_{ji}(\omega_k)$$

$$\frac{A_j(\omega_k)}{F_i(\omega_k)} = \frac{A_i(\omega_k)}{F_j(\omega_k)}$$

Equality Limitations

Ref.



j Hammer Impact positions

European Commission

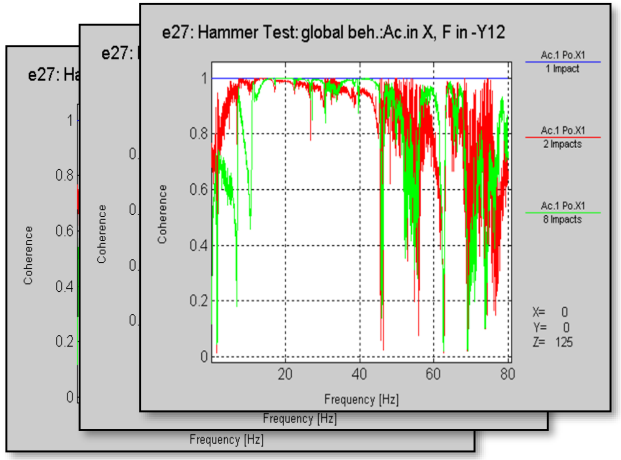
Control of the measurements

A first "Time Reduction" converting number of curves in few histograms

MATLAB: 1

Tenths or hundreds of coherence curves to check

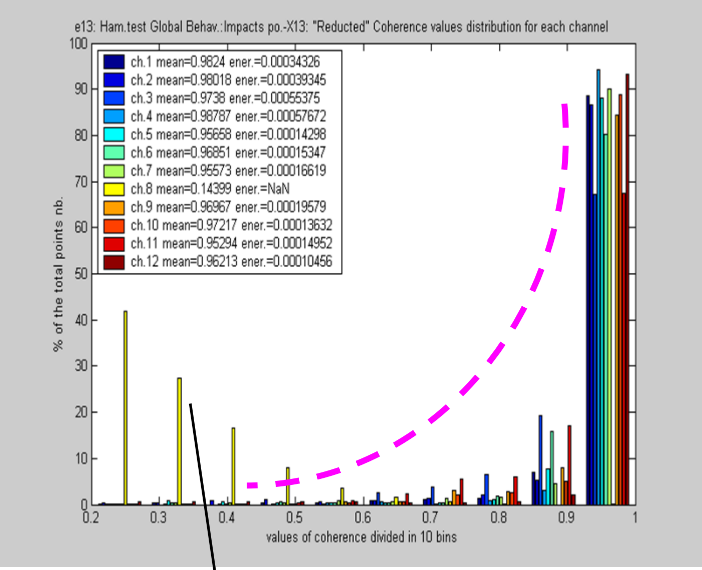
Coherence curves



Correct measurement

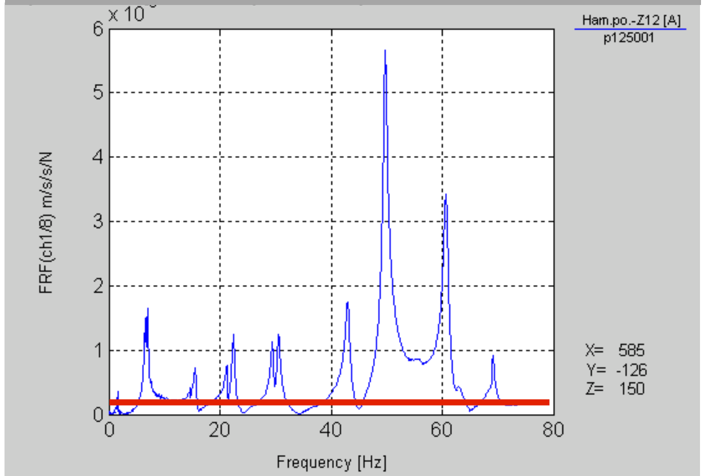
Represented by histogram of the coherence with a

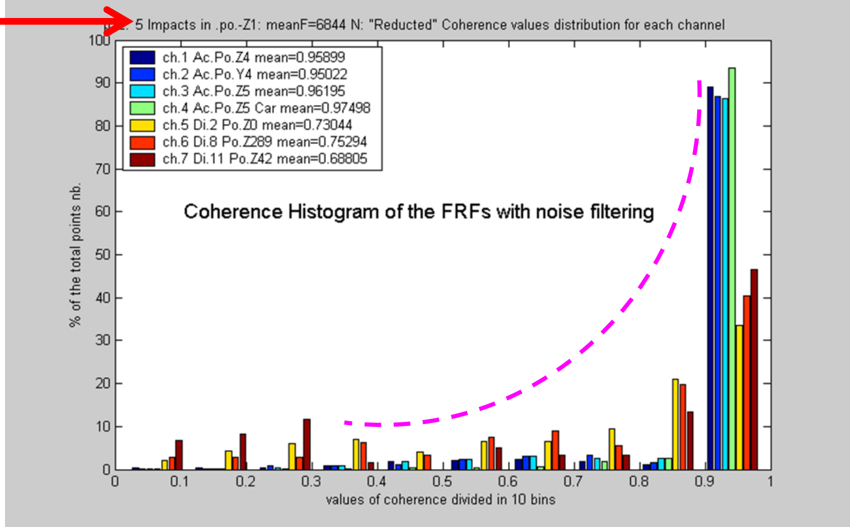
positive exponential fitting



After Noise filtering

FRF curves





Erroneous measurements ?

(on displacement transducer)

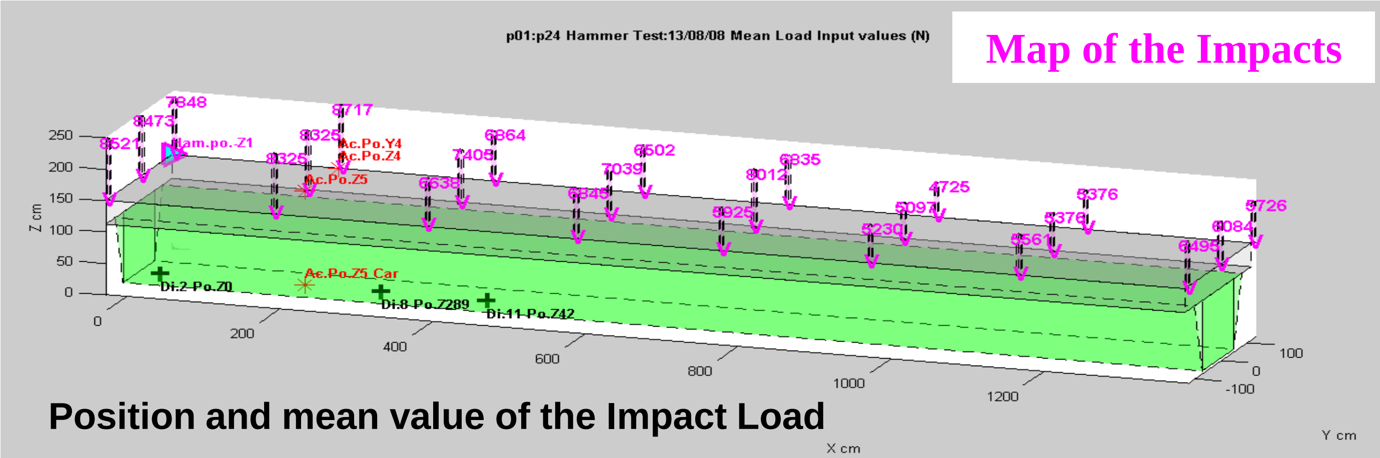
Spatial control of the measurements

MATLAB: 2

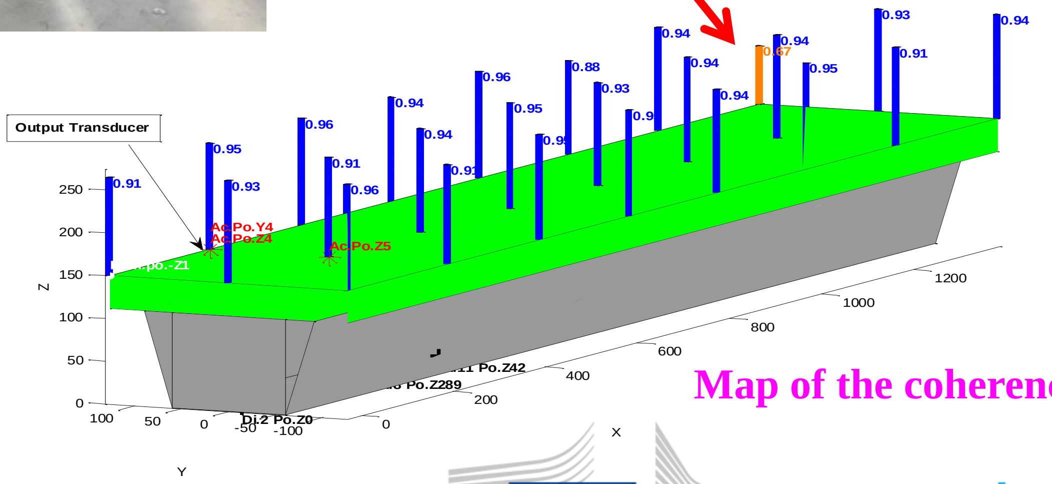
A Typical Example

Hammer tests on the first composite bridge of a motorway in Europe (Asturia -Spain)

Position to be controlled !



Position and mean value of the Impact Load



Map of the coherence

European Commission

Use of Macro for a fast 3D design of the structures

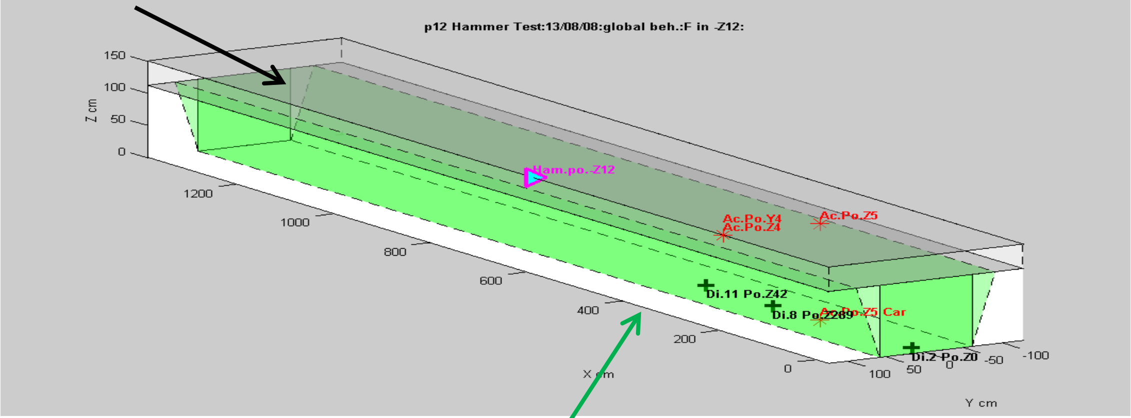
MATLAB: 3

Examples:

Bridge element in ELSA *(Prometeo project)*

Deck designed in grey color :

beam([-28 1385],[-126 126],[112 150],nf, [.6 .6 .6]);

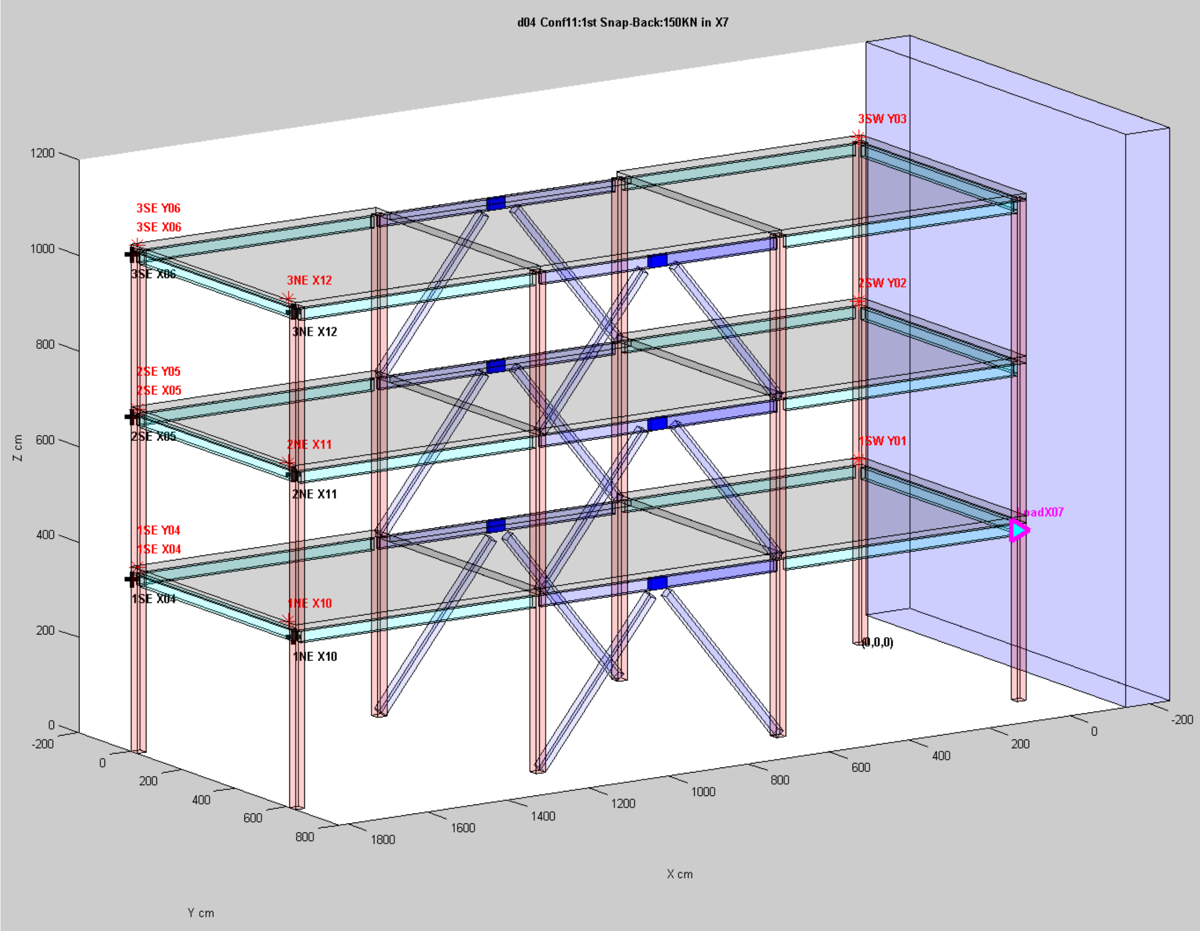


Carbon Beam with irregular section designed in green

irsbeam([-28 1385],[60 -60 -90 90 60],[0 0 112 112 0],12,'g')

([X], [Y], [Z], fig.Nb., color)

Design of a Building in ELSA (Duarem project)

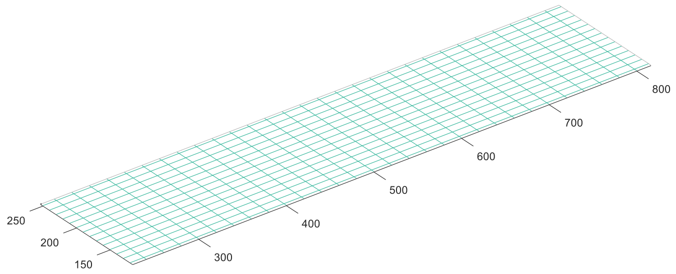


European Commission

Interpolations of irregular mesh of measurement positions

Color grid in correspondence with the vibration amplitude levels

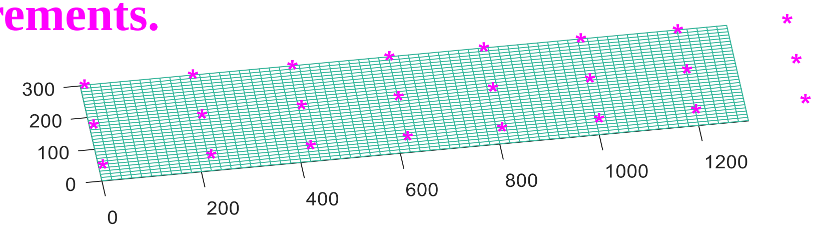
Ex: Prometeo Bridge Project



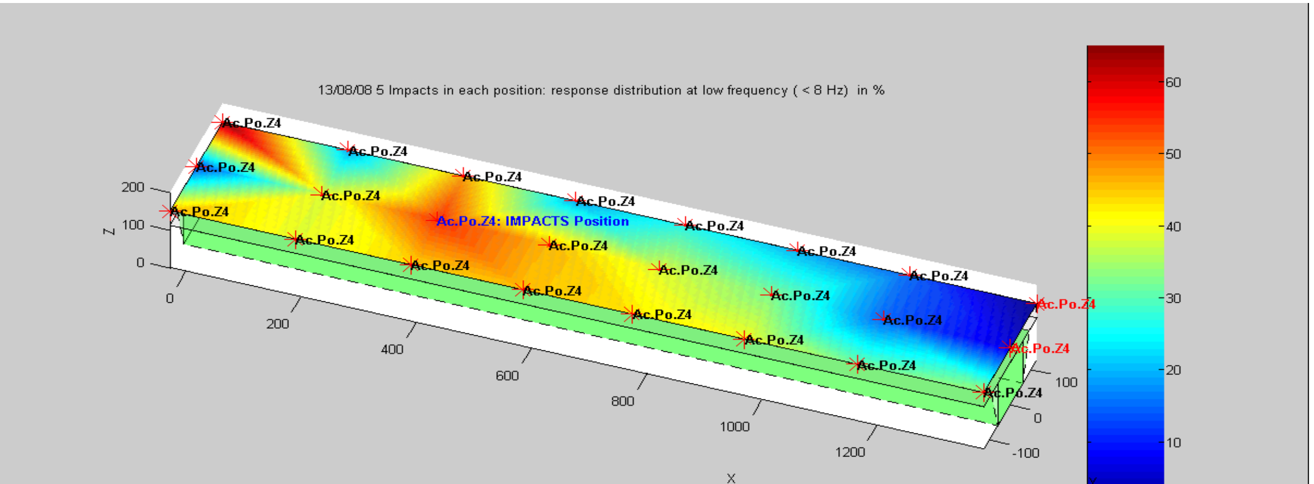
1- Create a regular cartesian mesh:

[xi,yi] = meshgrid(mi1:step1:ma1,mi2:step2:ma2)

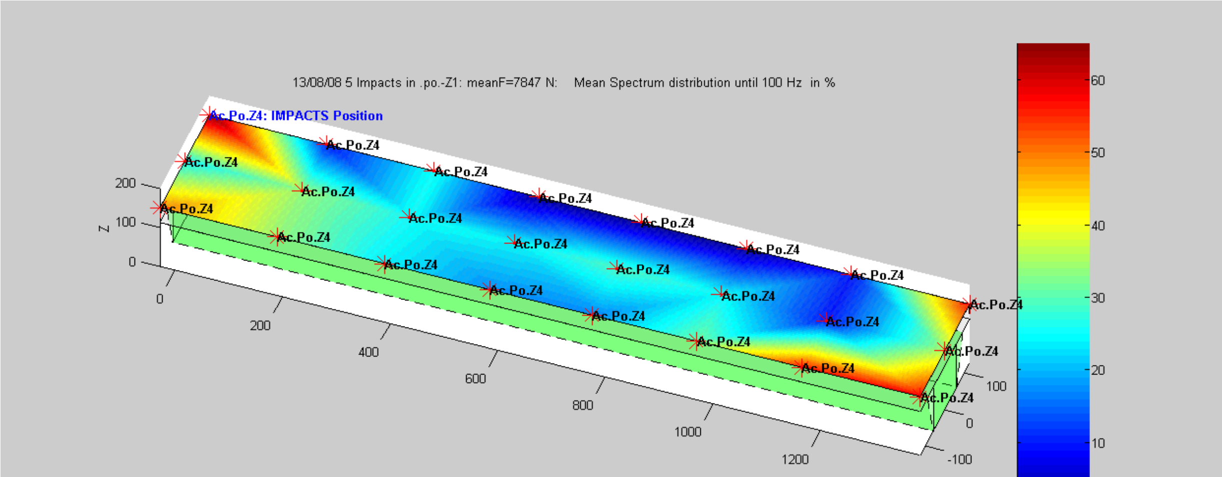
2-Interpolate the grid by the irregular distribution of measurements.



Produce an iso-surface with: *ci = griddata(Xcap1,Ycap2,Vcou,xi,yi);*



High frequencies distribution example: 10 Hz < f

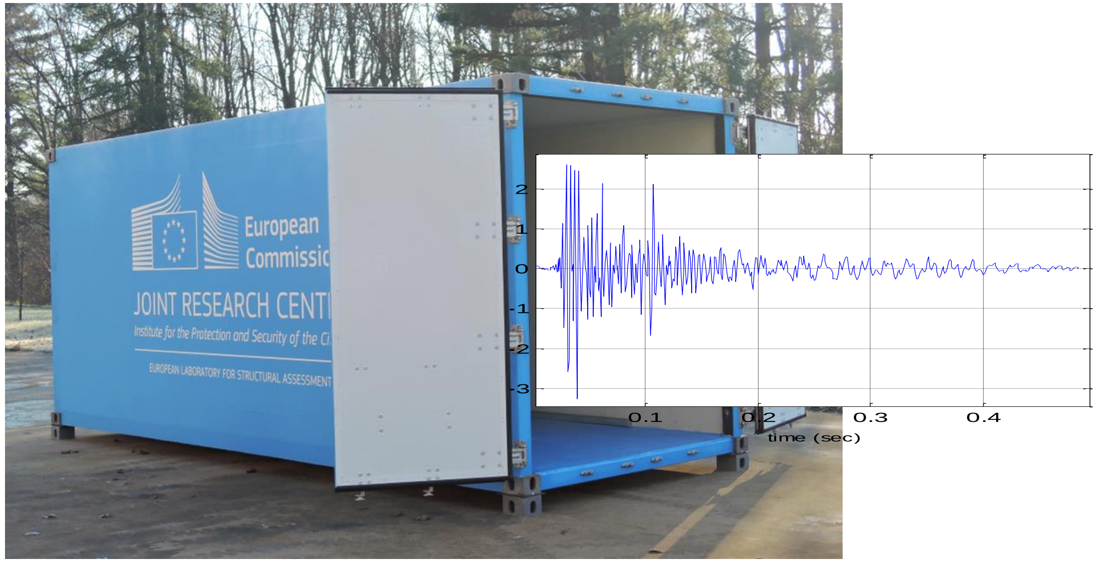


Low frequencies distribution example : 0< f <10 Hz

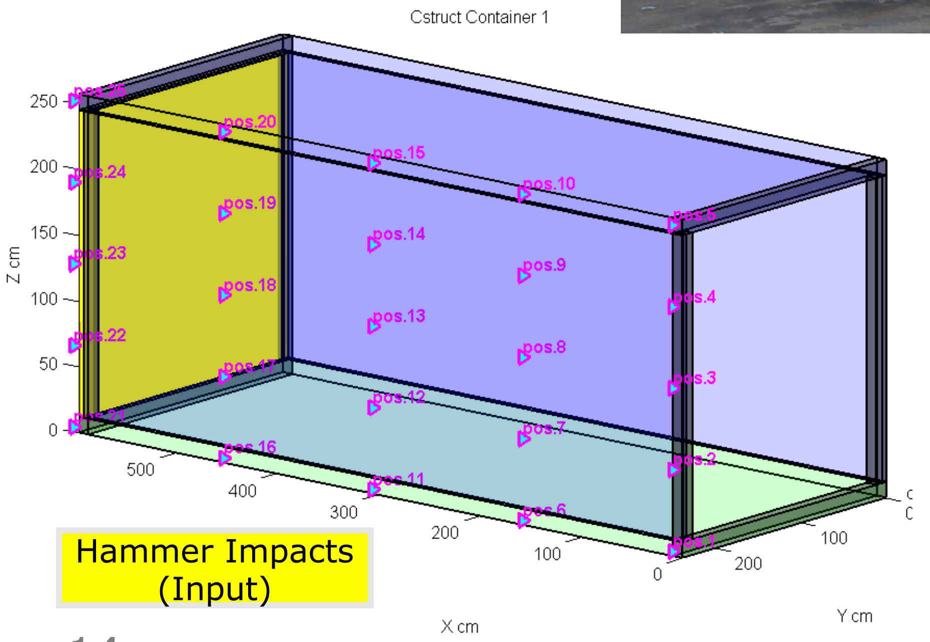
Example of structure to illustrate the process of modal parameters extraction: a smart composite container prototype

Vibrations

Induced by rain, wind, transportation, damaging etc..



Allows to measure the global mechanical properties of the container or one of its components.



Hammer Impacts (Input)

Signals in time domain

3 impacts at each position		3
25 positions for each panel	x	25
5 panels (each container)	x	5
3 transducers (Force+ 2 Acc)	x	3
Total: minimum time signals	=	1125

European Commission

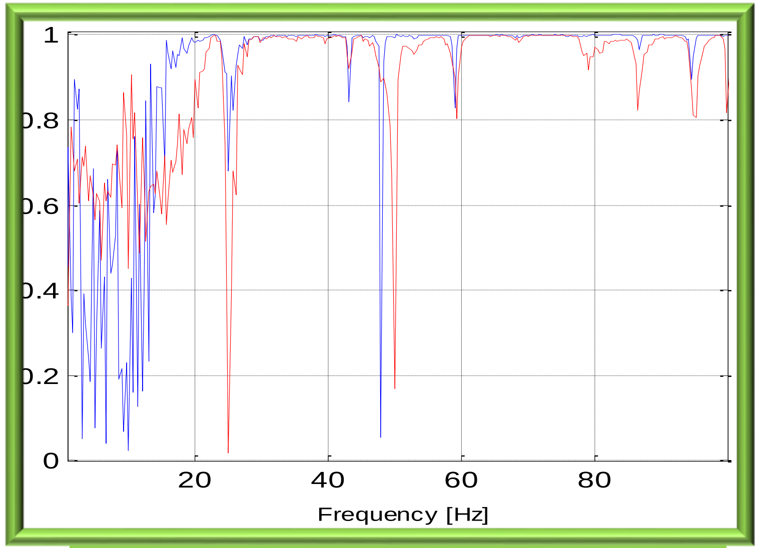
Signal processing to obtain modal parameters

From Time domain (1125 signals) to

Frequency domain (Fourier Transform)

Control of the data

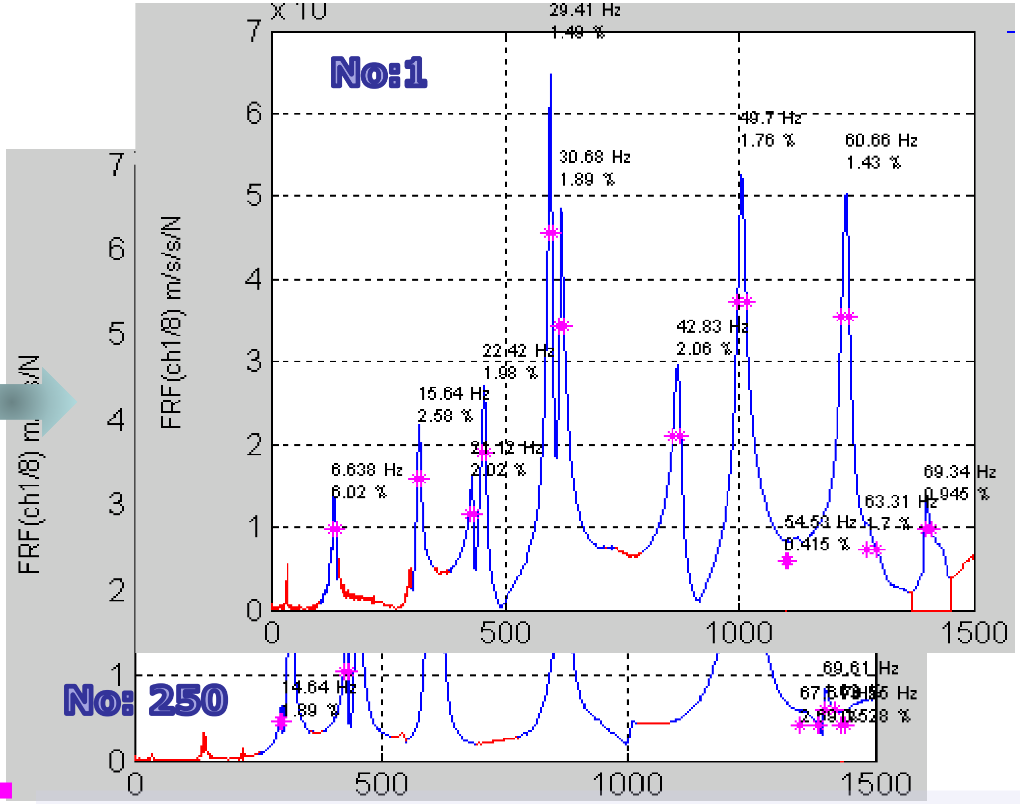
Physical interpretation of the data



250 Coherences functions
("control" of the measurements)

Matlab, step:5

Algorithm of automatic identification of 3 parameters of each peak in the experimental and noisy 250 curves, and display of the results in a few seconds



(125 positions*2 Outputs) =250 FRFs files

250 vectors of different dimensions

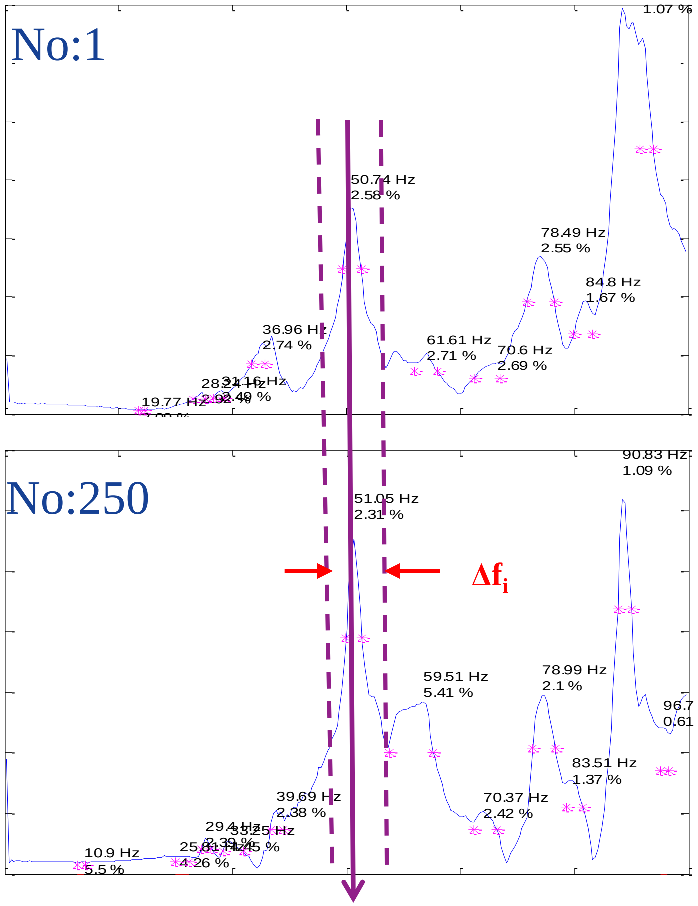
3 ×

Frequency
Amplitude
Damping

Optimisation to obtain the final modal parameters

MATLAB EXPO 2018

250 frequency vectors



Clustering in m_i modes

Δf_i : **Mf**

$$\begin{pmatrix} mf_{11} & mf_{12} & \cdots & mf_{1m} \\ mf_{21} & mf_{22} & \cdots & mf_{2m} \\ \vdots & \vdots & & \vdots \\ mf_{n1} & mf_{n2} & \cdots & mf_{nm} \end{pmatrix}$$

1 column for each frequencies cluster found

MATLAB, step:6 (fastening with matrix)

$$Mf_1 \begin{pmatrix} mf_{11} & mf_{12} & \cdots & mf_{1m} \\ mf_{21} & mf_{22} & \cdots & mf_{2m} \\ \vdots & \vdots & & \vdots \\ mf_{n1} & mf_{n2} & \cdots & mf_{nm} \end{pmatrix} \text{ 250lines } \bullet\bullet\bullet \quad Mf_n \begin{pmatrix} \; \end{pmatrix}$$

m_1 **col.** m_n **col.**

For each window dispersion Δf_i : 1 Frequency Matrix Mf_i

Which is the best clustering?

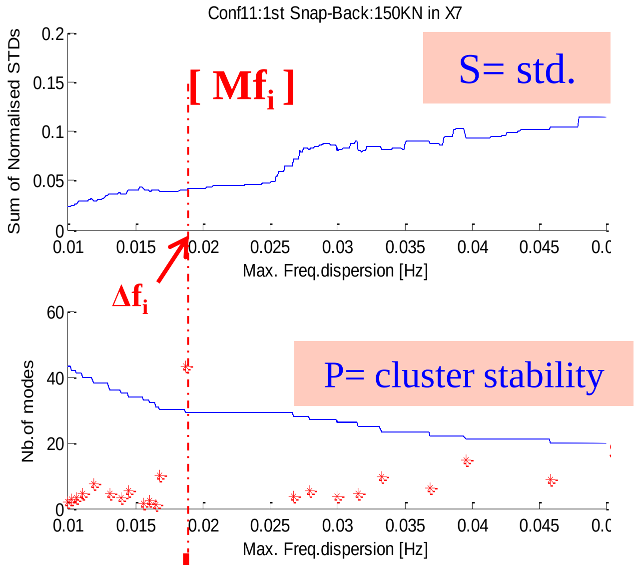
Calculate for each Δf_i, a Statistic S, and a Physical parameters P:
S=Mean Std. Deviation for all columns (modes)
P= Stability of the cluster (modes) when Δf_i increases.

Solution in the set of frequency matrix

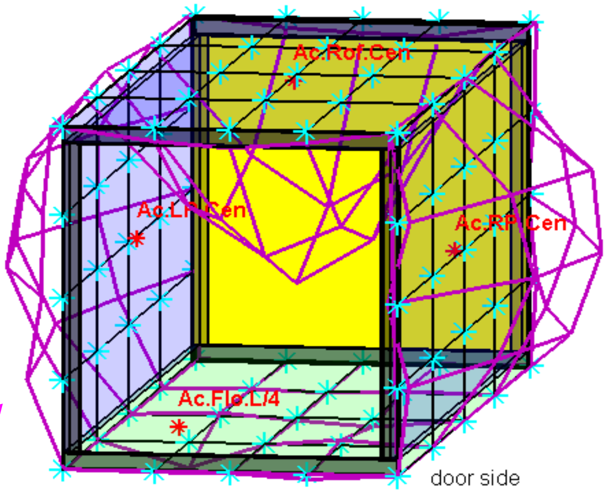
= Max(P/S)

European Commission

Solution of the modal parameters extraction



Mode shapes



CSTRUCT

25 Highest modes/FRF.
Minimum of. 8 values/mode
Freq.Dispersion limits=0.3 to 1.3(Hz)
Results from Output n: Acc4,

Solution Number:1
Df<1.0470 Hz

Mode Nb.	Freq. (Hz)	Damp. (%)	Fre.Disp. (%)
01	8.3104	8.052	7.274
02	22.764	1.089	1.422
03	26.791	3.728	3.139
04	29.280	1.766	3.144
05	31.301	2.537	2.179
06	35.294	2.548	2.250
07	39.343	2.580	1.655
08	42.393	1.480	1.315
09	44.491	2.301	1.803
10	63.185	1.554	1.629
11	66.269	1.445	1.047
12	90.515	1.329	0.713

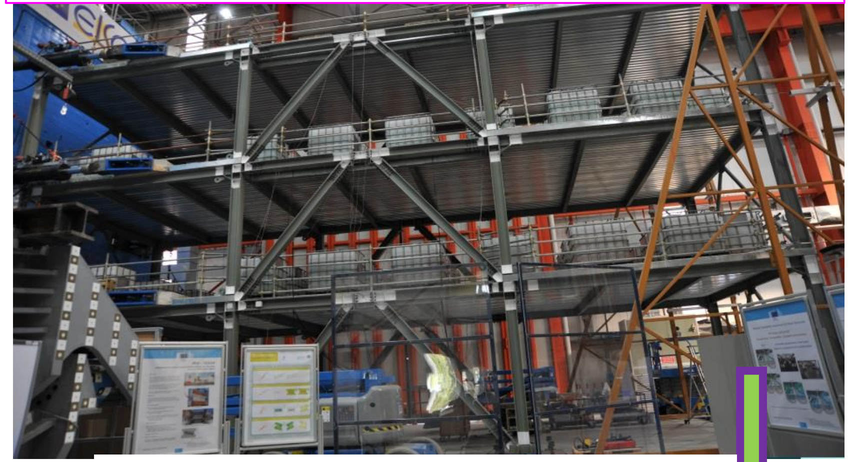
Solution Number:2
Df<0.7830 Hz

Mode Nb.	Freq. (Hz)	Damp. (%)	Fre.Disp. (%)
01	8.3104	8.052	7.274
02	22.764	1.089	1.422
03	26.738	3.537	2.147
04	29.297	1.717	1.325
05	31.301	2.537	2.179
06	42.393	1.480	1.315
07	44.390	2.096	1.664
08	66.257	1.433	0.801

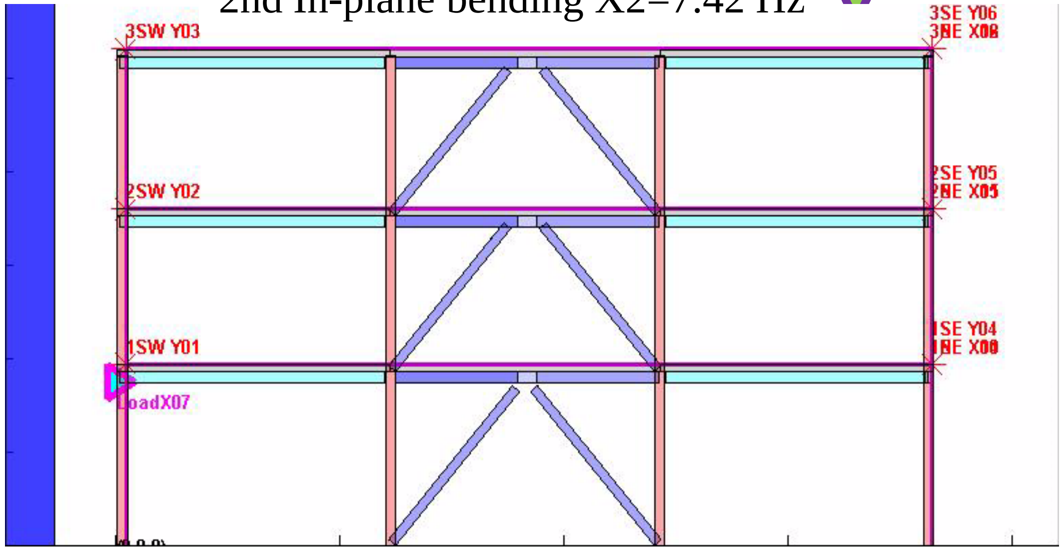
Solution Number:3
Df<0.4830 Hz

Mode Nb.	Freq. (Hz)	Damp. (%)	Fre.Disp. (%)
01	22.764	1.089	1.422
02	26.666	3.648	0.801
03	29.297	1.717	1.325
04	29.357	1.622	1.185
05	31.268	2.470	1.125
06	42.400	1.473	1.175
07	66.397	1.447	0.633
08	90.575	1.367	0.418

Other Example: Duarem Frame in ELSA



2nd In-plane bending X2=7.42 Hz



Sig.Processing: Danbox3
daniel.tirelli@jrc.ec.europa.eu

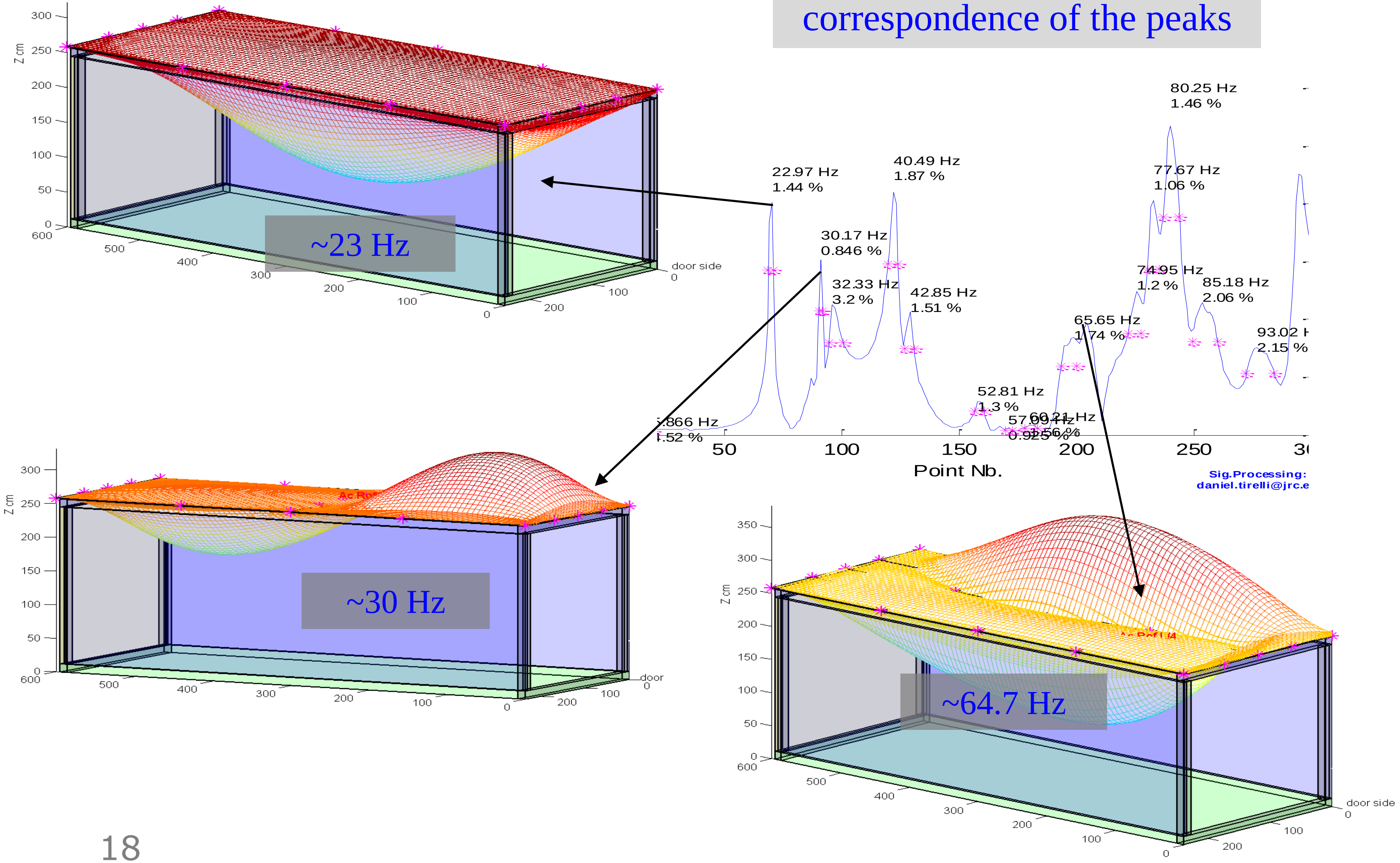
Spline interpolation for a better shape interpretation

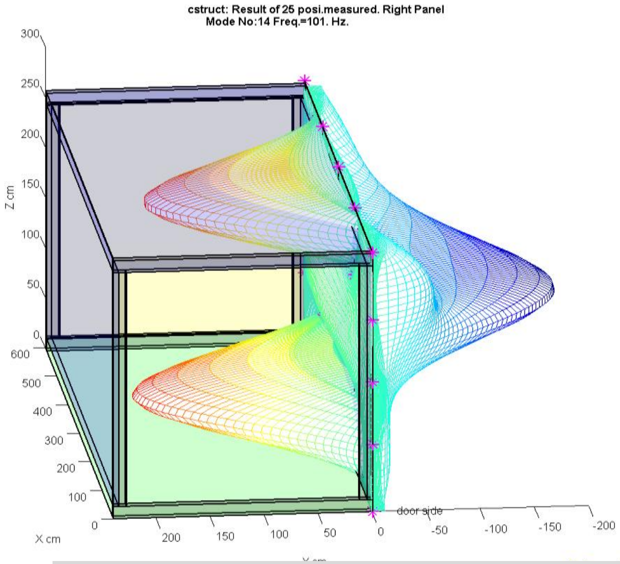
MATLAB EXPO 2018

MATLAB, step:7

[xi,zi] =ndgrid([…],…
yi = interpn(X',Z',Y',xi',zi','spline');

Example of the main mode shapes of the roof panel in correspondence of the peaks

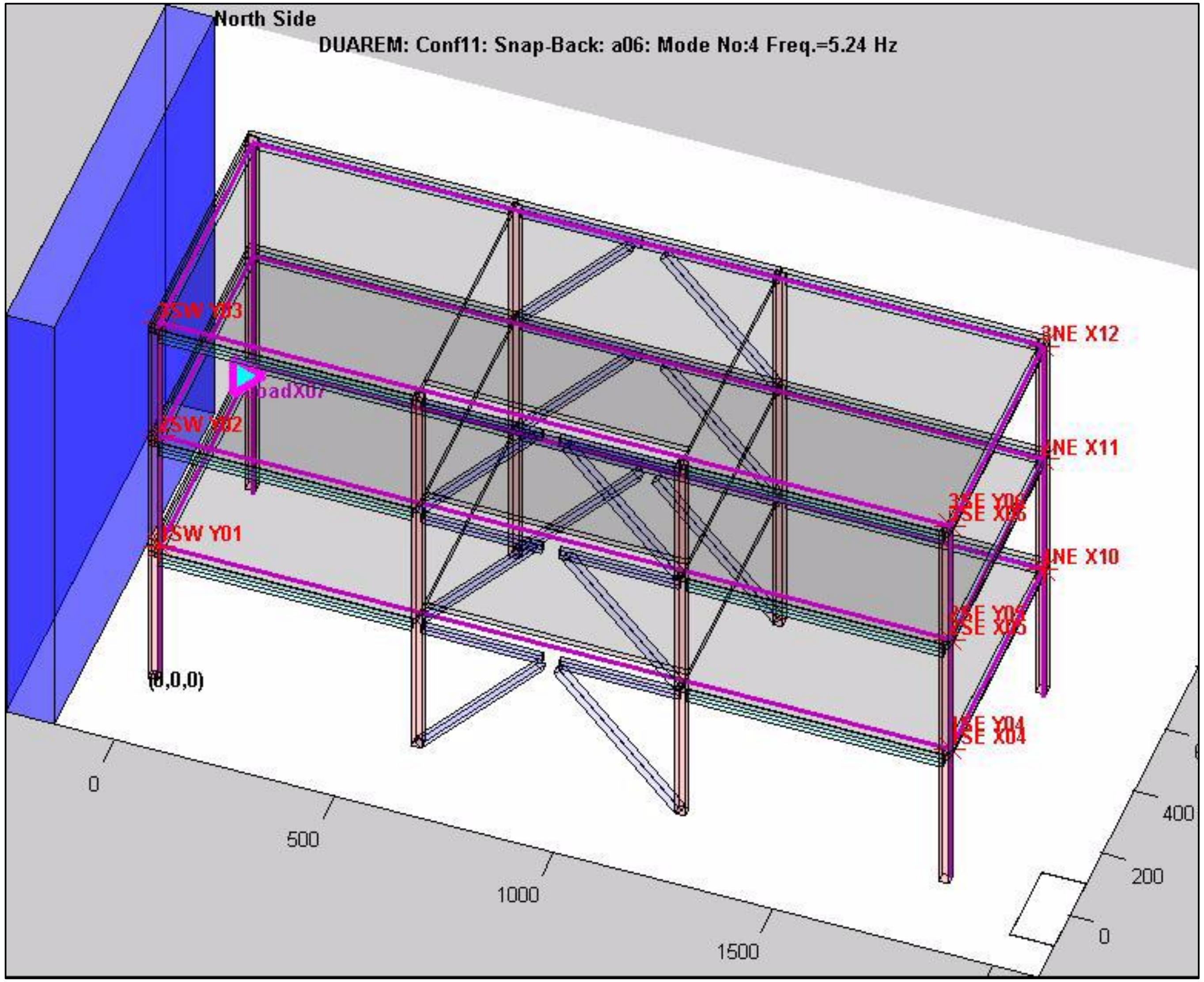


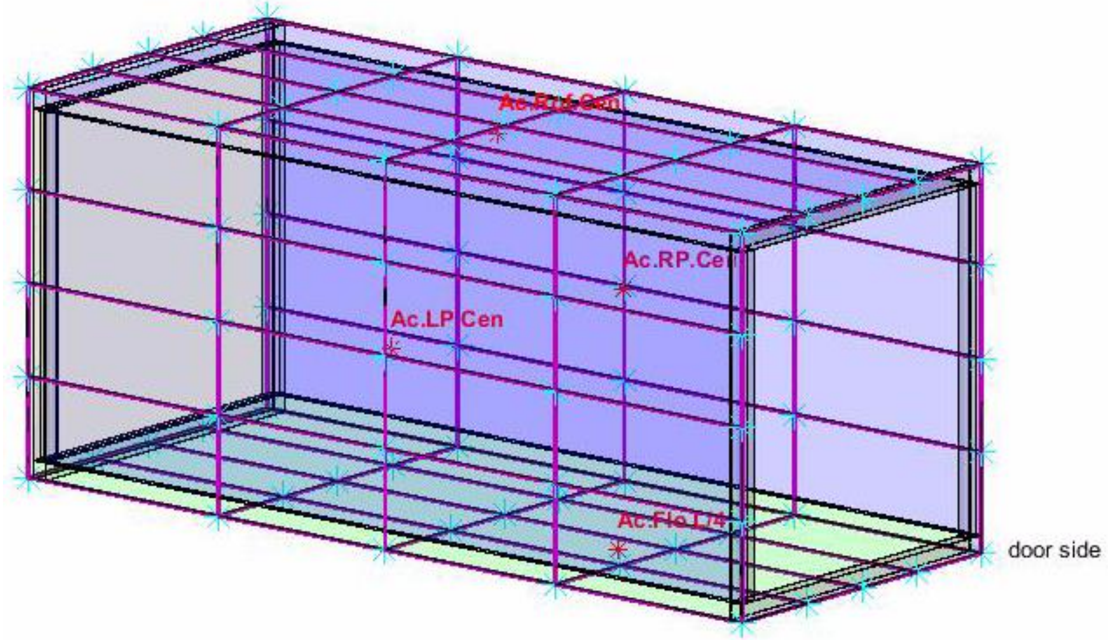


Example of a mode shapes of one of the vertical panel

European Commission

Results recorded in video format without interpolation

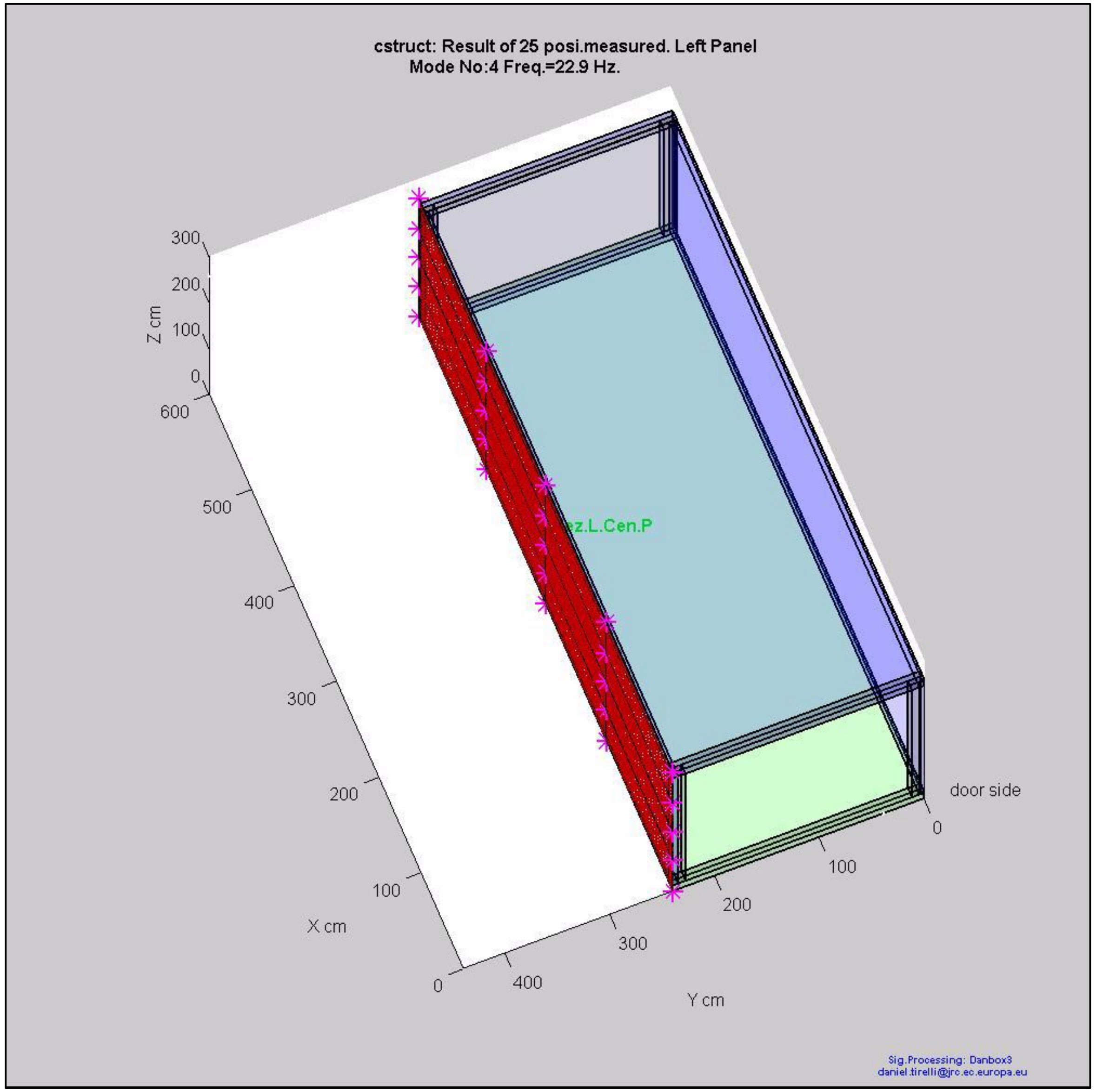


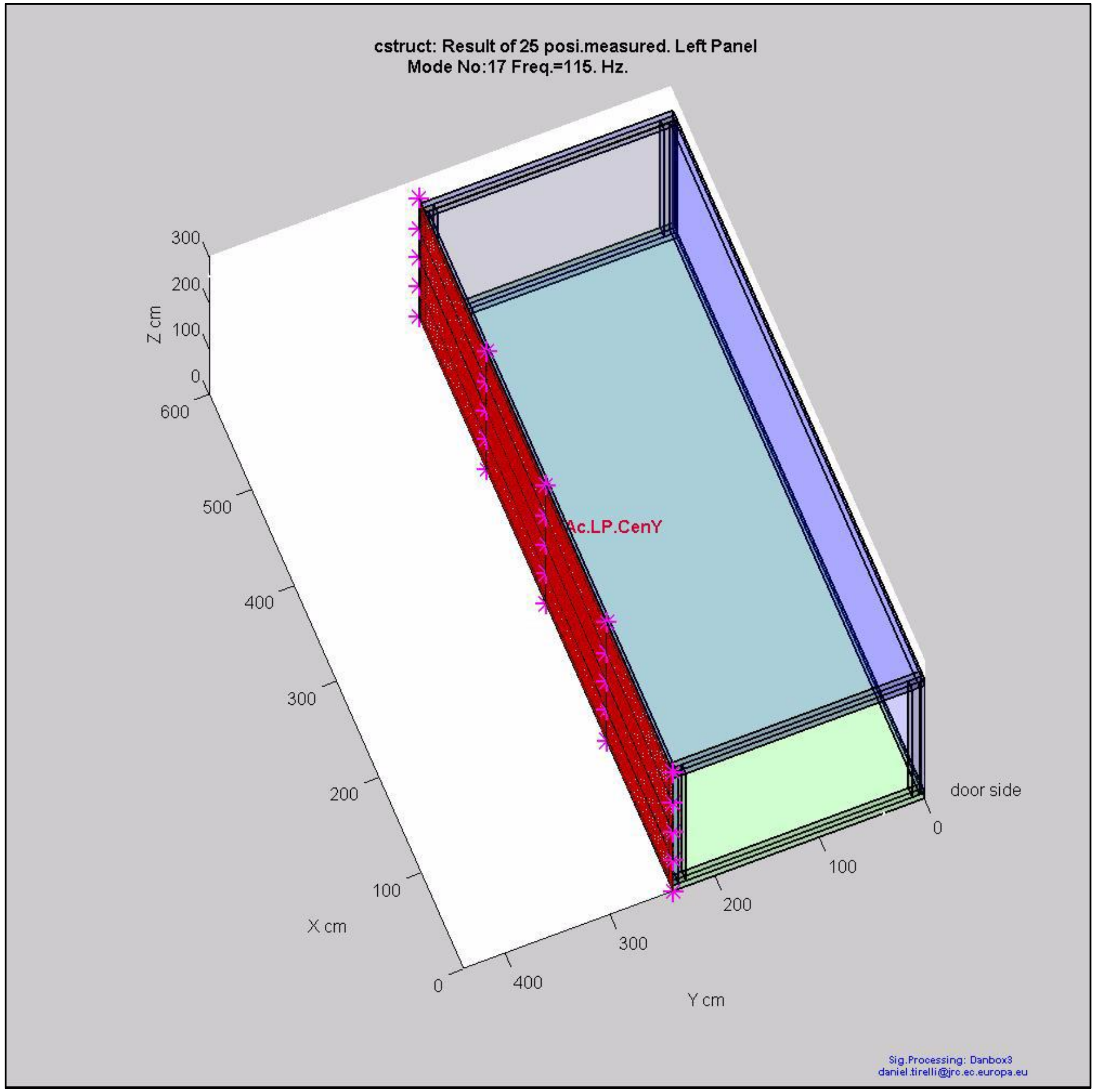


European Commission

Results recorded in video format with interpolation

MATLAB, step:8





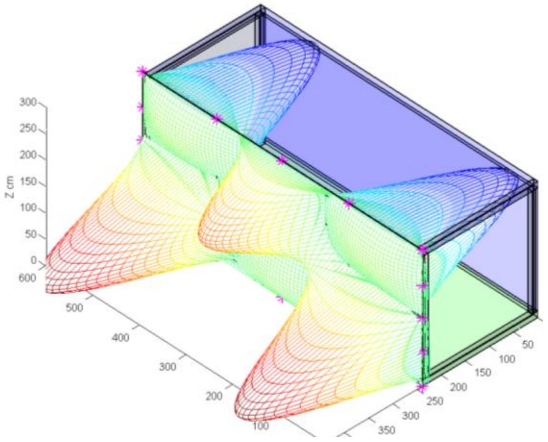
MATLAB EXPO 2018

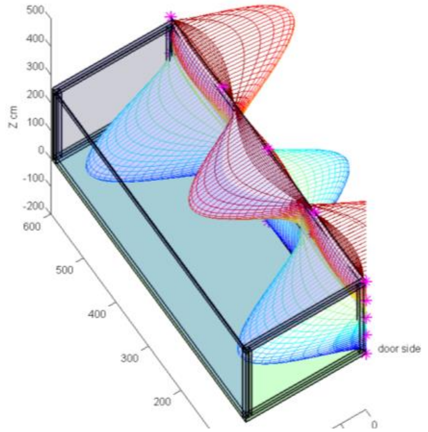
Use and Interpretation of the Results: examples

Stiffness comparaison:

Left panel stiffer than the right panel fl > fr

Left Panel fl~77,2 Hz





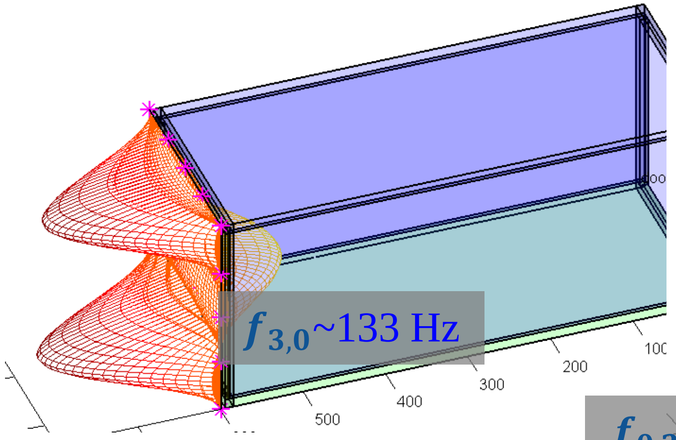
Right panel fr ~ 72,3 Hz

Comparison with theory of thin plates:

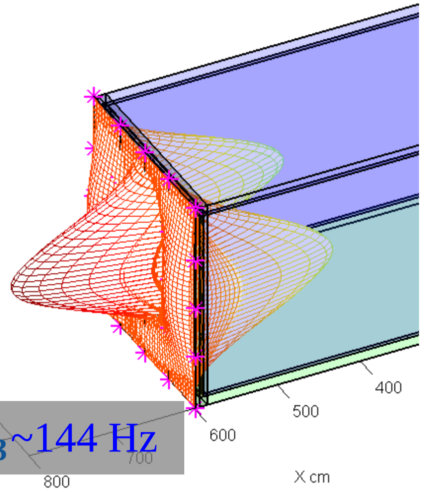
in agreement with the theory

Theory of thin plates

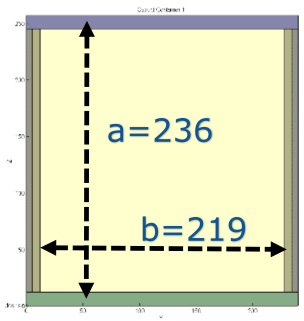
$$f_{m,n} = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$



$f_{3,0}$~133 Hz



$f_{0,3}$~144 Hz



Mode ratio	Freq.ratio Exp.	Freq.ratio Theo.
Y2/Z2	1.066	1.077
Y3/Z3	1.08	

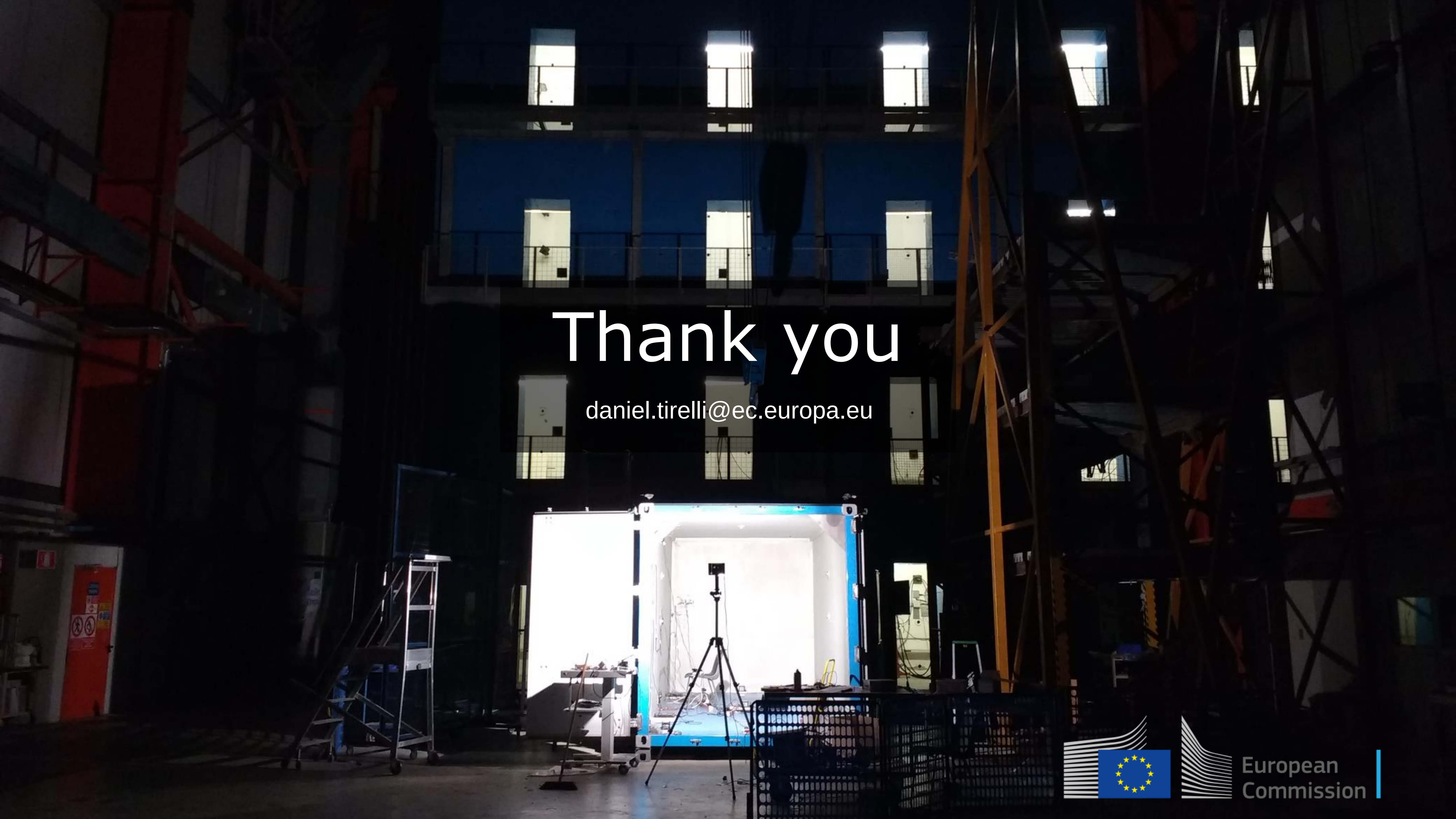
European Commission

Conclusions

The methodology allows the experimental modal analysis based only on measurements processing, with structured automated steps.

Automatisation of:

- **Near Real-time Signal Processing** during the tests for measurements control.
- Possibility to adopt **Fast Hammer Testing** method (faster method)
- **Spatial control** of the measurement to immediately detect the errors locations.
- **Powerful Interpolation** to control and for a great help in the interpretation of the results.
- **3D Visual animated** representation of the results.



Thank you

daniel.tirelli@ec.europa.eu

European Commission