FROM VIBRATIONS
TO IDENTIFICATION

VIRTUAL SHAKER TESTING AT V2I: MEASURED-BASED SHAKER MODEL AND INDUSTRIAL TEST CASE

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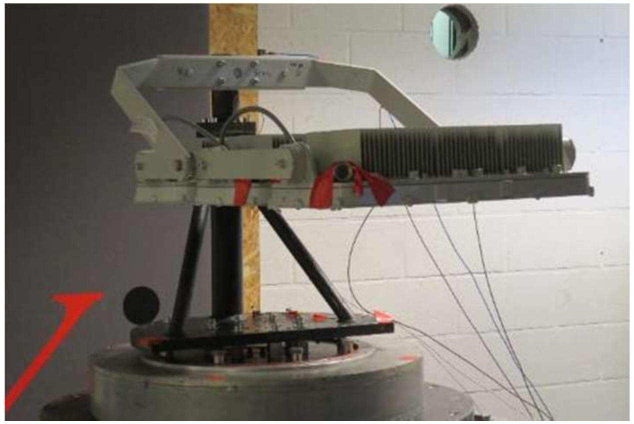
Simulation of the vibration test can be useful

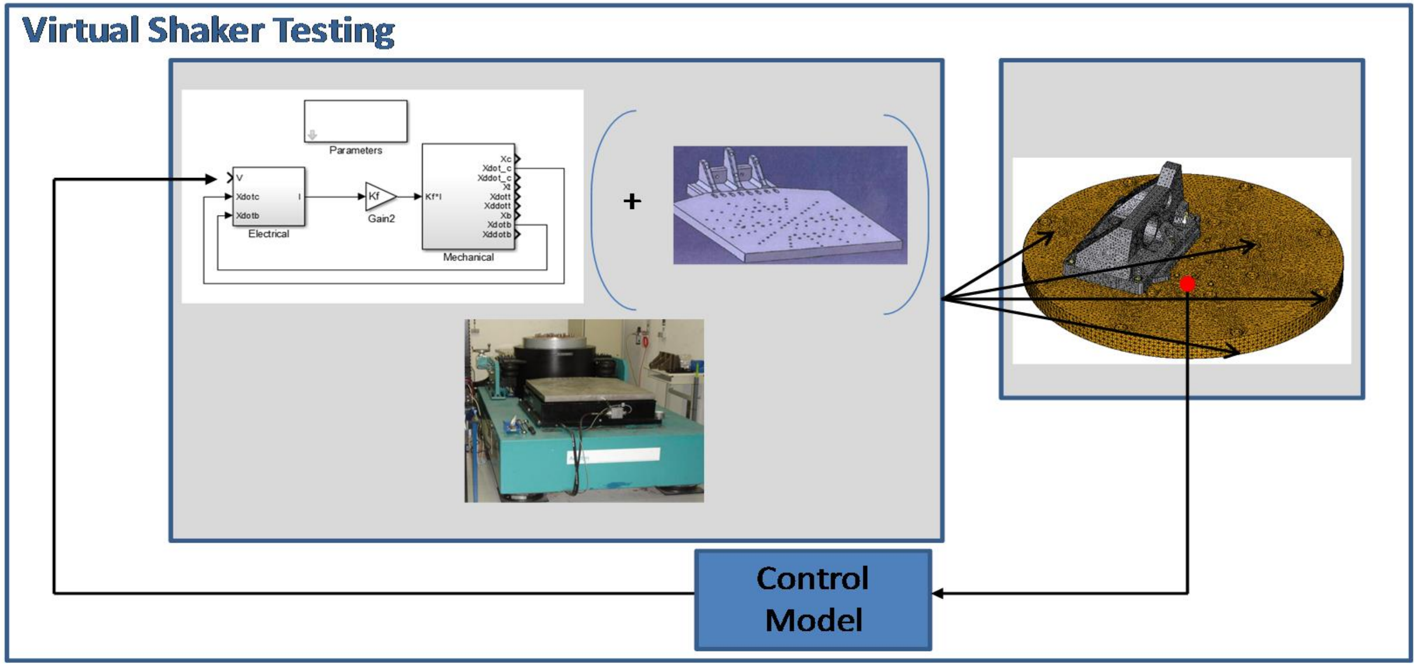
- Heavy structure
- High imposed loads
- Centre of gravity misalignment
- Anti-resonance



Can induce undesirable behaviour (beating, transversal load, over or under testing,…)

Tools allowing to simulate the coupled system (specimen, shaker and controller) help the test engineer to foresee the difficulties and look for solutions.

All the parts play a role in the Virtual Shaker Testing



From measurements via modelling to validation

1) Virtual Shaker Simulator
   a. Shaker functioning
   b. Electromechanical model
   c. System identification
   d. Model updating
   e. Controller model
   f. Specimen coupling

2) Validation on test cases

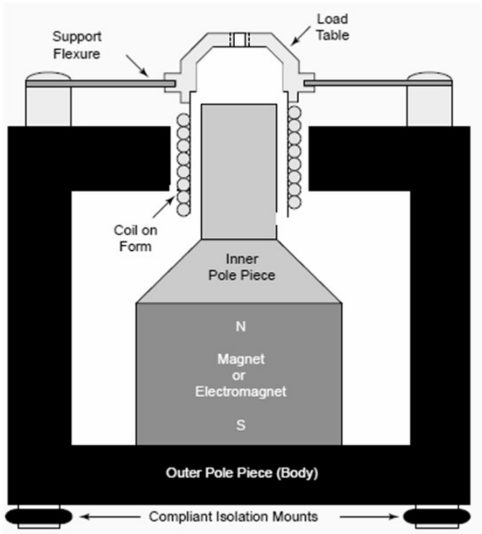
Shaker similar to a robust loudspeaker

Coupled electromechanical system

- Magnetic circuit + current through the coil = vertical force
- Velocity of the coil within magnetic field = back EMF

Limitations:

- At low frequencies: maximal displacement
- At intermediate frequencies: maximal velocity linked to maximal current
- At high frequencies: maximal forces and voltage



G. Fox et al., *Understanding the physics of electrodynamic shaker performance*, Sound. Vib, Oct. 2001

7 +1 degrees of freedom model …

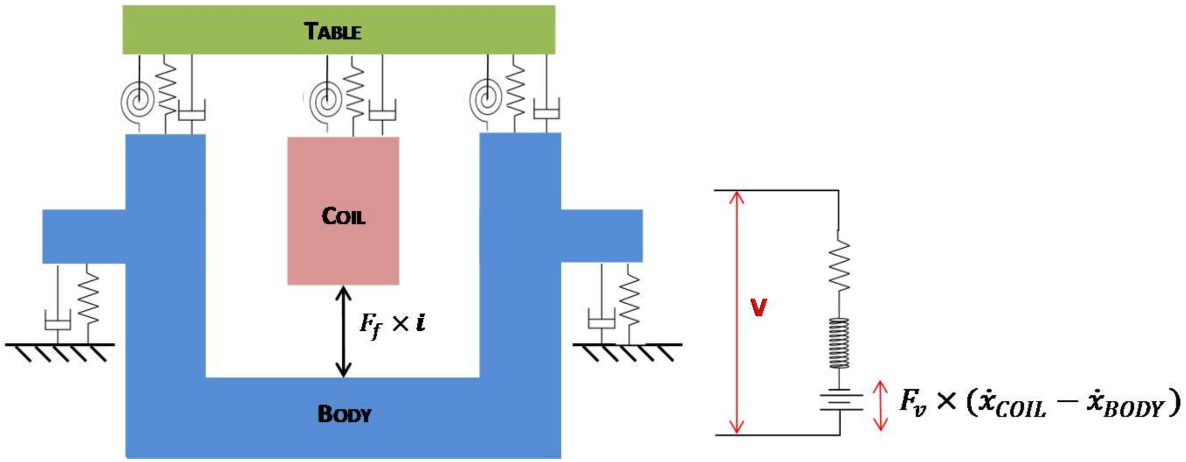
$$F = B\, l\, n\, i = K_F\, i$$

$$E_{bemf} = B\, l\, n\, \dot{x}_{coil} = K_F\, \dot{x}_{coil}$$

$$\boldsymbol{x} = [z_{Coil} \quad z_{table} \quad z_{body} \quad \boldsymbol{\theta}_{z,table} \quad \boldsymbol{\theta}_{x,table} \quad \boldsymbol{\theta}_{y,table} \quad \boldsymbol{\theta}_{z,Coil}]^T$$

$$\boldsymbol{q} = [\boldsymbol{x} \quad i]^T$$

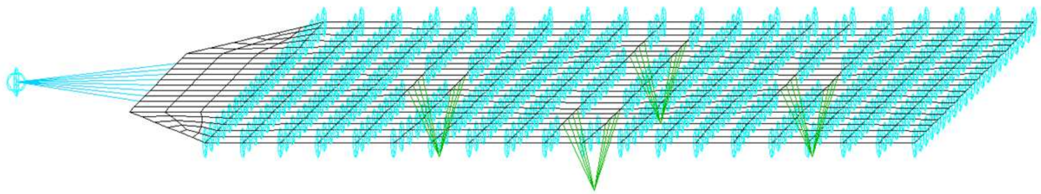
$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{0} \\ \boldsymbol{0} & 0 \end{bmatrix} \ddot{\boldsymbol{q}} + \begin{bmatrix} \boldsymbol{C} & \boldsymbol{0} \\ \boldsymbol{F}^T & L \end{bmatrix} \dot{\boldsymbol{q}} + \begin{bmatrix} \boldsymbol{K} & -\boldsymbol{F} \\ \boldsymbol{0} & R \end{bmatrix} \boldsymbol{q} = \begin{Bmatrix} 0 \\ V \end{Bmatrix}$$



… linked to the slip table finite element model

Shaker can be rotated and coupled to a slip table

Finite element model (*Samcef*):
- Table: shell element
- Oil effect: spring element
- Bearing: spring/damper element



Measurements taken as basis for the model updating

For both vertical and horizontal configurations:

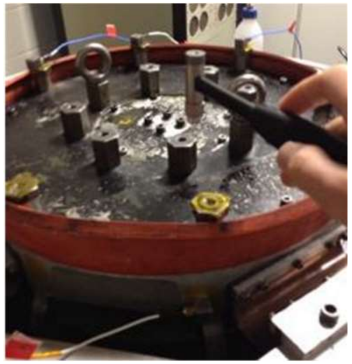
- Hammer impact testing
- Low level sine sweep [5-2500 Hz]

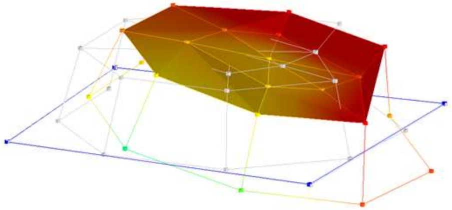
Data needed for the model updating:

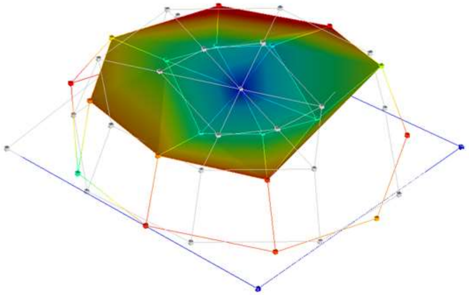
- Modal characteristics: resonance frequencies, modal shapes and damping ratios
  - For vertical configuration:
    - *Coil mode*
    - *Suspension mode*
    - *Rotation modes* of the table (in-plane and torsion)
    - *Isolation mode* (below frequency of interest)
  - For horizontal configuration:
    - *Pumping mode*
- Electromechanical coupling and RL system parameters identification

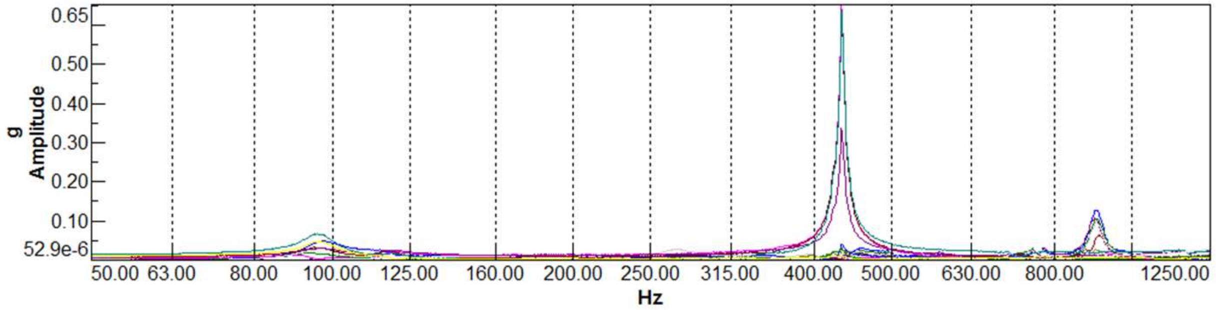
Rotation modes identified

- Coil mode not properly detected during impact testing
- In-plane rotation mode
- Torsion mode
- Rotation modes also observed during sine sweep
- Highly sensitive to the suspension mounting



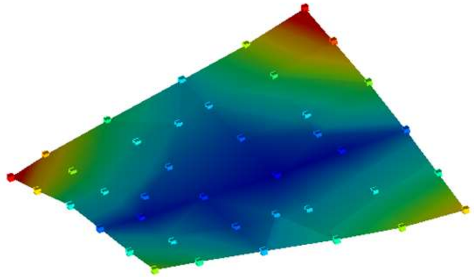




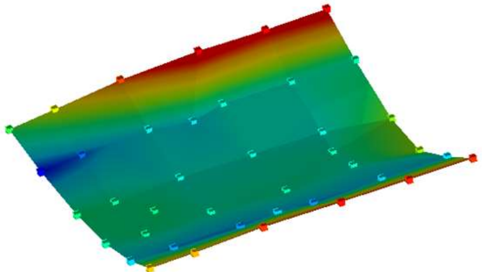


Complex dynamic of the slip table

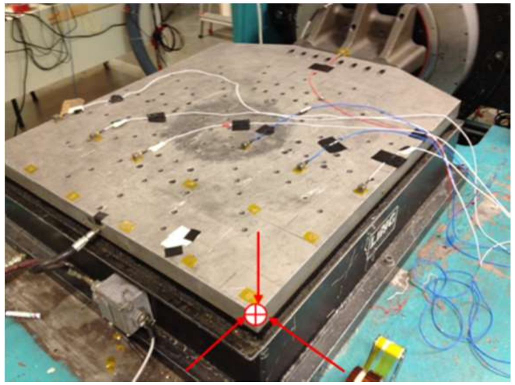
- Pumping mode identified thanks to modal analysis (shaker at rest) and sine sweep (shaker on)
- Pumping mode detected at lower frequency with sine sweep

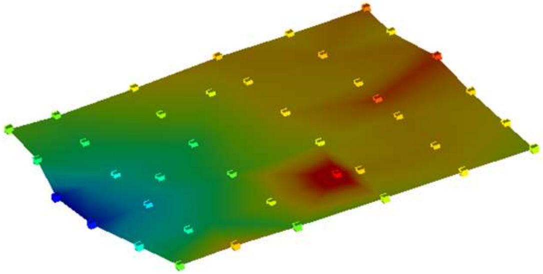


528 Hz – 1,9 %

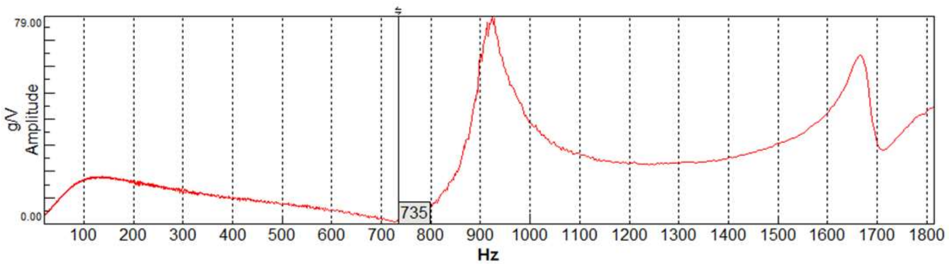


691 Hz – 1,5 %





886 Hz – 1,0 %



Model updating strategy

- For the vertical configuration, initial values for the masses, the stiffnesses, the resistance and inductance from data sheets
- For the horizontal configuration, measurement of the geometrical dimensions
- Updating performed by manual sensitivity analyses

In order to:

- Represent the modal content: frequencies, mode shapes and damping ratios
- Minimize the differences between measured and simulated frequency response functions

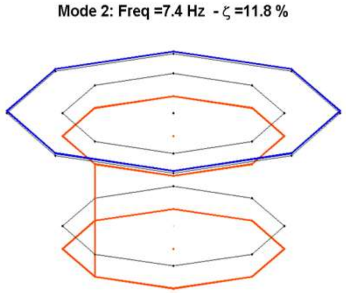
The effort is focused on the features potentially involving undesirable effects (coil mode, pumping mode, torsion mode,…)

Additional works (measurements and updating) have to be done to achieve a model with a better level of correlation

Model updating: vertical configuration

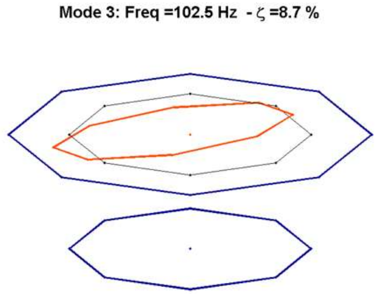
Suspension Mode

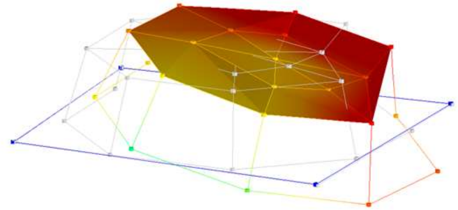
- Non-measured
- Tuned based on data sheet data



In-Plane Rotation

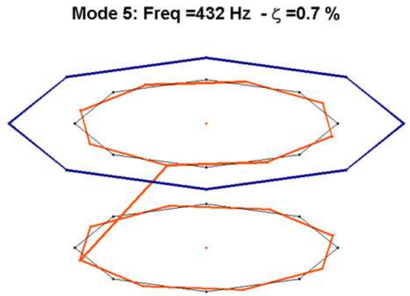
- Twice (symmetrical)
- High level of damping

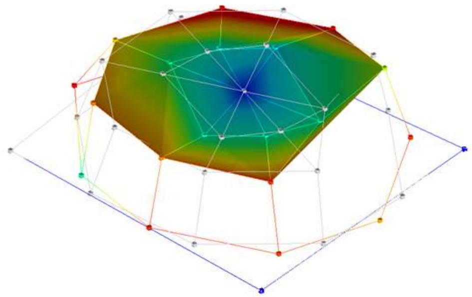




Torsion Mode

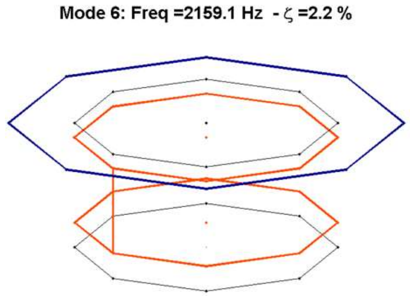
- Low level of damping
- Supposed to be out-of-phase mode





Coil Mode

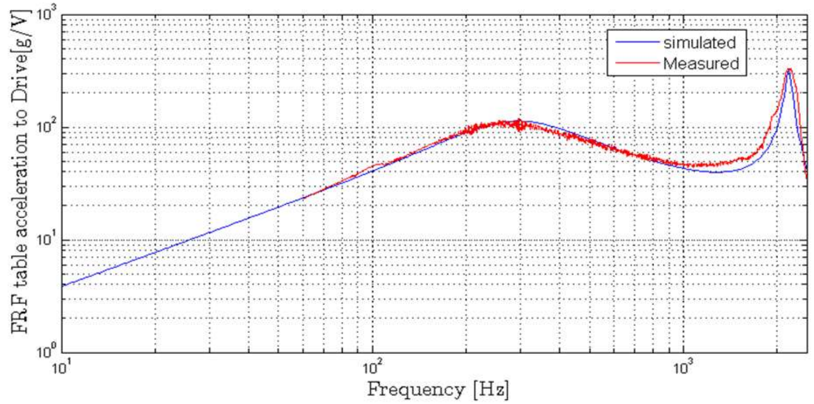
- Detected on sine sweep measurements
- Coherent with data sheet



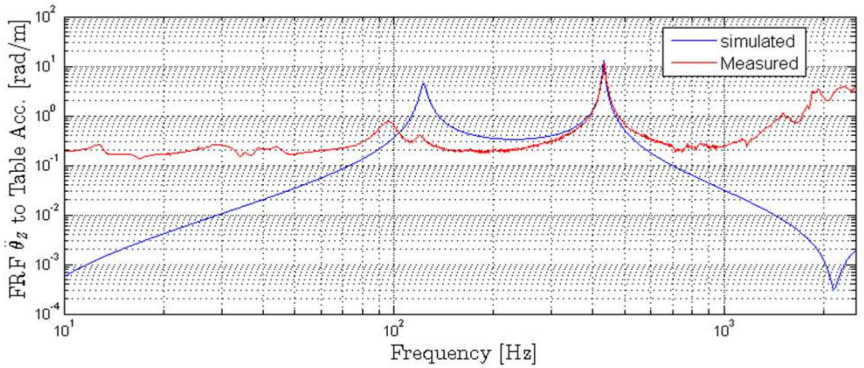
Model updating: vertical configuration

Electrical parameters and coupling coefficient *F* updated thanks to table vertical acceleration to drive voltage FRF

Correlation satisfactory to represent the shaker dynamic



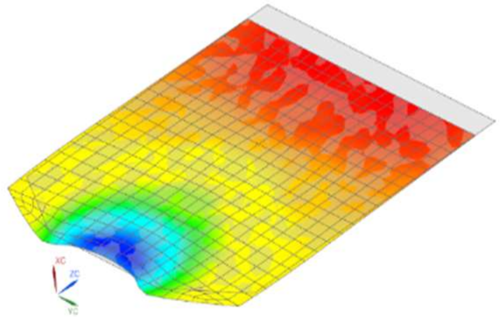
Comparison between measured and simulated table vertical acceleration to drive voltage Frequency Response Function



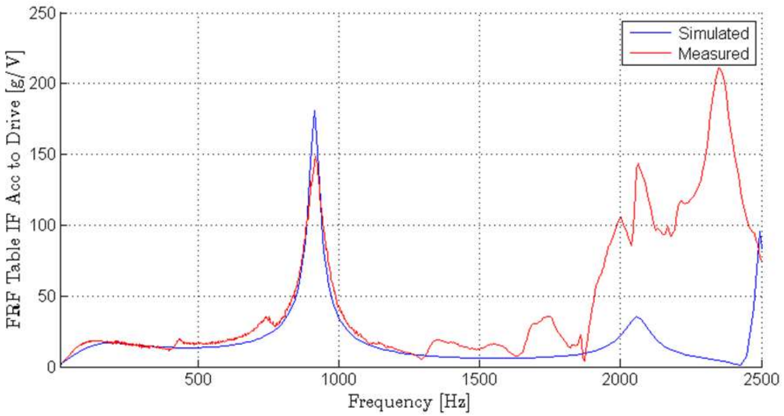
Comparison between measured and simulated table acceleration (rotation around the vertical axis) to table vertical acceleration Frequency Response Function

Model updating: horizontal configuration

- Pumping mode correlated (to modal analysis when shaker at rest)
- Difficulty to achieve satisfactory level of correlation (MAC < 0,7) for the other slip table modes due to the difficult representation of the oil effect

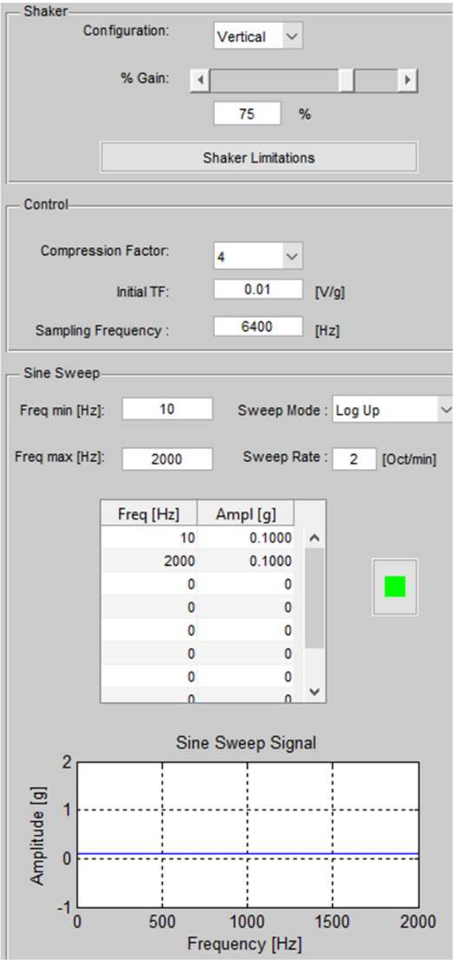


Mode 881 Hz



Controller that mimic the LMS hardware

- Controller model created and validated by Siemens LMS team
- Allowing to simulate sine sweep
- Available control parameters:



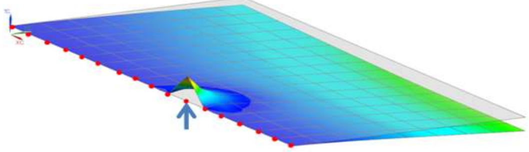
Reduced-order model coupled to the system

Assuming that:

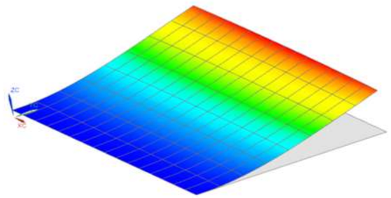
- A finite element model of the specimen is available
- Modal characteristics are known (ideally with the specimen fixed on the shaker in test configuration): frequencies, mode shapes and modal ratios
- Updated model is performed

the procedure to integrate the specimen model to the shaker model is :

- Define a master node rigidly linked to the specimen interface
- Compute a Craig-Bamptom super-element: retained Dofs of the master node (vertical translation and rotation) and number of modes to have sufficient effective masses in the frequencies range of interest



Constrained Modes



Internal Modes

Reduced-order model coupled to the system

- Link the reduced model of the specimen to the shaker table Dofs by imposing the compatibility and equilibrium conditions

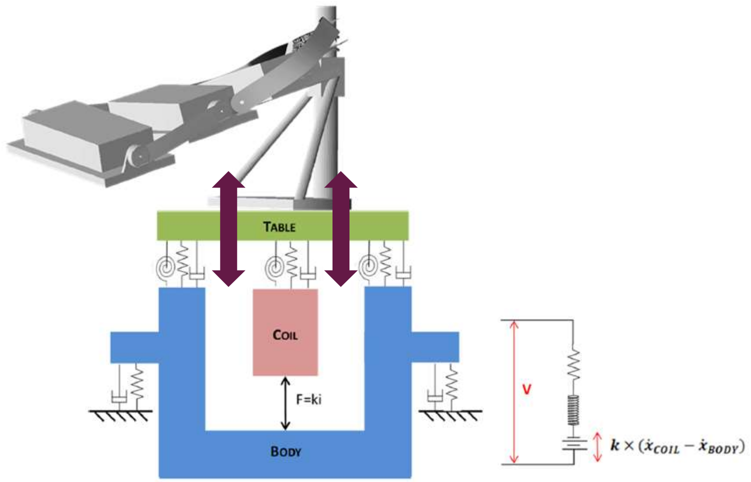
Compatibility

$$q_{spe\ i} = q_{table_i} \text{ with i} = 3, 4, 5 \ \& \ 6$$

Equilibrium

$$F_{reac:specimenToShaker} + F_{reac:ShaketToSpecimen} = 0$$

$$\text{with } F_{reac} = \underbrace{\left\{ M_{FI} \times \left[-\frac{K_{II}}{M_{II}} \quad -\frac{C_{II}}{M_{II}} \right] \right\}}_{C} \times \begin{Bmatrix} p \\ \dot{p} \end{Bmatrix} + \underbrace{\left\{ M_{FI} \times \frac{M_{FI}}{M_{II}} \right\}}_{D} \times \ddot{q}_F$$



Simple beam to validate the procedure

Steel 30x30x4x4 mm beam clamped on the shaker head

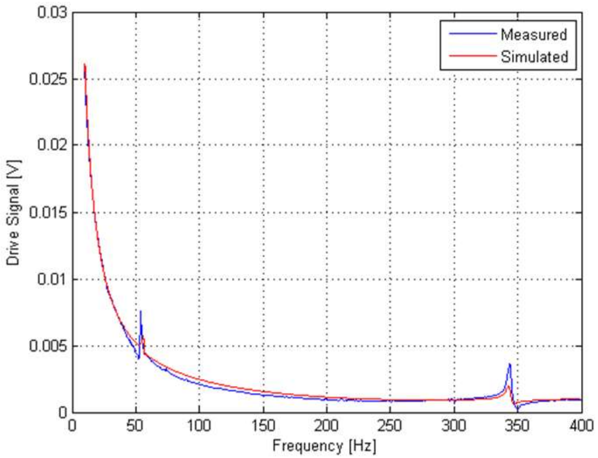
Modal characteristics identified:
- 0,9% of damping for the 1B modes
- 0,3% of damping for the 2B modes

Finite element model updated:
- Beam elements

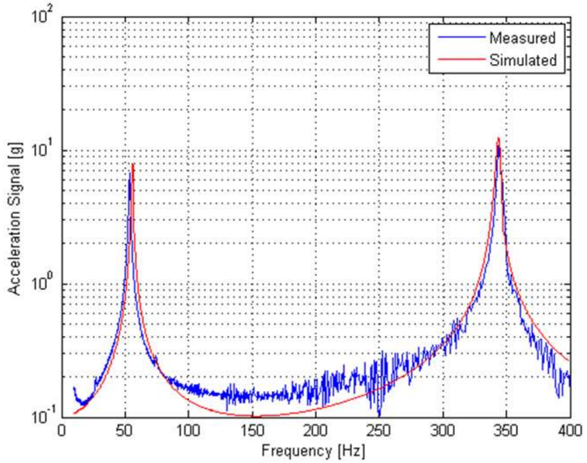
Two control point locations tested:
- At the beam basis
- At the beam centre

Good prediction of the coupled system

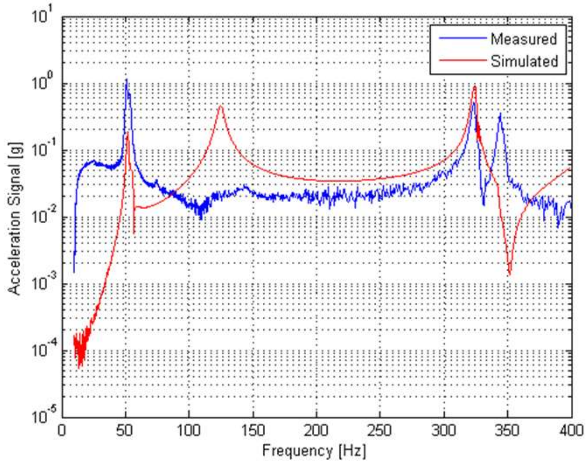
1) Control point at the beam basis



Drive Voltage



Vertical acceleration at beam tip

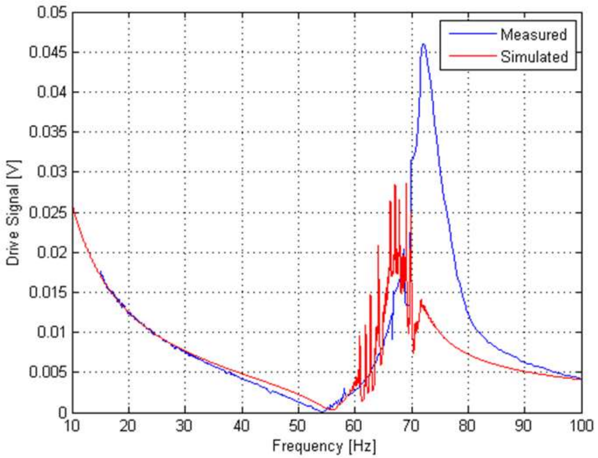


Transverse acceleration at beam tip

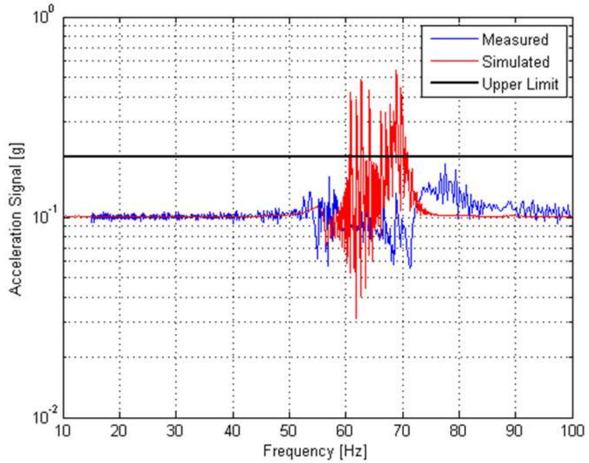
Difficulty predicted when control on antiresonance

2) Control point at the beam centre

- During the physical test, control parameters have been modified to be able to pass the antiresonance frequency



Drive Voltage



Vertical acceleration at beam tip

Industrial structure can be tested

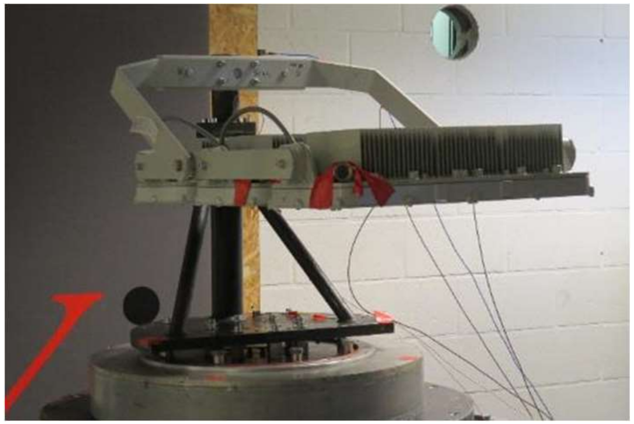
Luminaire designed and commercialized by Schréder

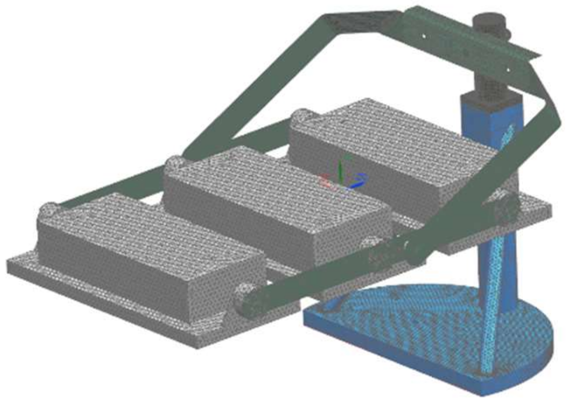
Finite element updated:

- 650 000 dofs
- Assembly of parts by face gluing and rigid body elements (RBE)
- Modal damping percentage determined

Qualification test according to IEC norm:

- 0,5 g imposed at the luminaire fixation at first resonance frequency
- Sine sweep between 5 and 55 Hz

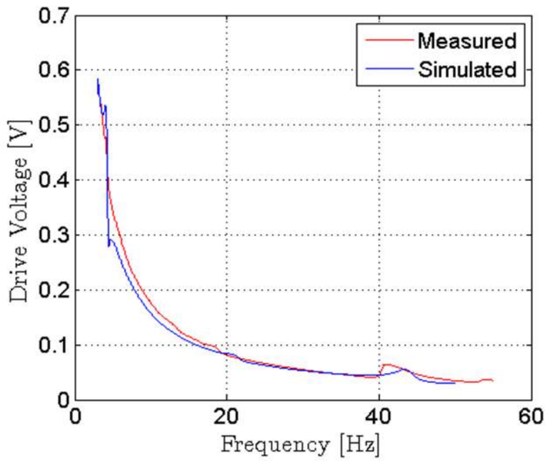




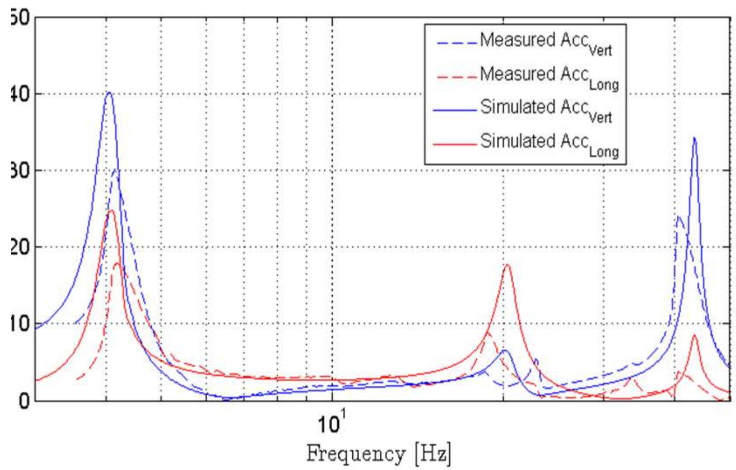
Industrial structure can be tested

Simulation duration: 580 s to be compared to the 240 s of physical test

Non-linearity observed at around 40 Hz (opening of the fork assembly)



Drive Voltage



Acceleration at CoG

Conclusions

All blocks of the virtual shaker are created and assembled:
- 7 + 1 degrees of freedom model for the electromechanical model of the shaker
- Controller model supplied by Siemens LMS
- Reduced-order model of the specimen allows dealing with industrial structure (modal characteristics needed to update the finite element model)

Additional studies has to be performed to improve the slip table model

Validation on two test cases: the dynamic of coupled system is accurately predicted

Control parameter modification can be tested to deal with detected difficulties

Additional functionalities such as the control on average on several points are planned to be implemented

Thank you !

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