An Overview of Combined Experimental and Numerical Approaches for Spacecraft Vibration Test Simulation

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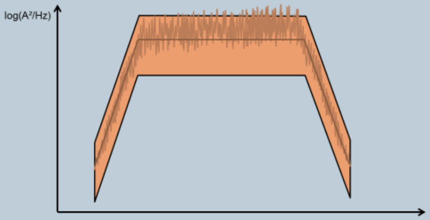
Introduction and Objectives

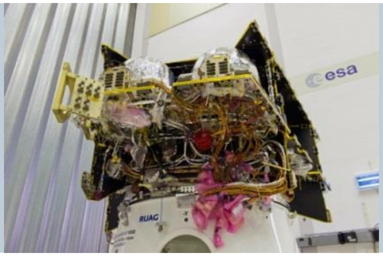
Objectives of Spacecraft Vibration Testing

… on shaker testing facilities …

1. **To ensure, demonstrate the spacecraft (S/C) integrity during launch and operational loads.**
2. **Validate S/C FEM for reliable Coupled Load Analysis with launcher.**

Arianespace, *www.arianespace.com*
European Space Agency (ESA), *www.esa.int*





Different boundary conditions in flight (6DoF, flexible adapter), classical FEM (6DoF, cantilever conditions with base excitation), and test (1DoF, dynamical interaction with vibration shaker system)

Over/under-testing, poor correlation with mathematical models → **Expensive delays, component pre-aging or even damage** → **Virtual Shaker Testing**

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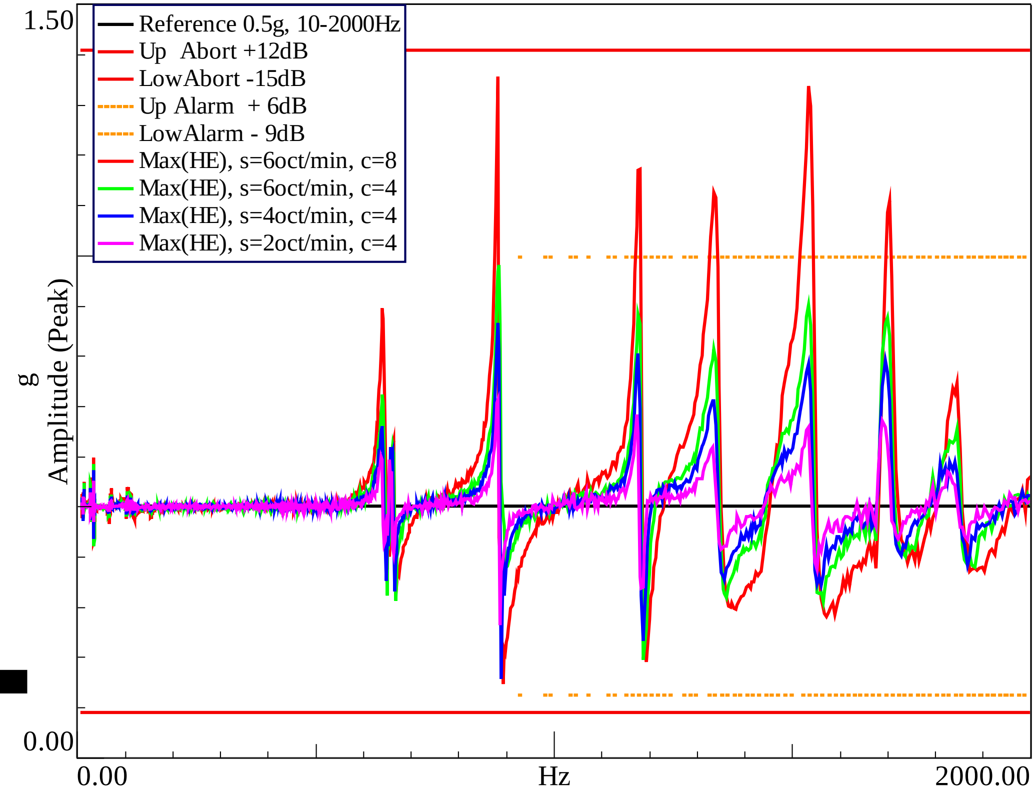
Laboratory Motivation

- How does the test setup/specimen behave in the *sine vibration* laboratory test ?
- Are there any risks for the test specimen, testing facility, …?
- How to increase the test/control performance by changing initial parameters ?



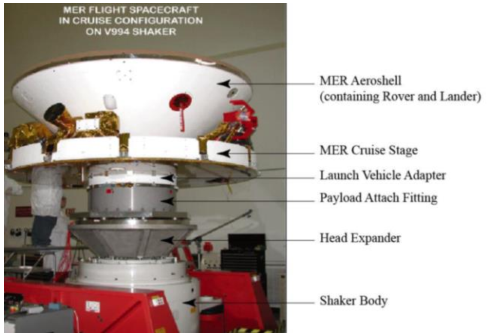
Virtual Shaker Testing
(Numerical Test Simulation)

Introduction and Objectives

What do we mean by 'Virtual Shaker Testing'

For ESA 'Set of Facility Simulation Tools'

- Simulation of vibration test runs before and during their executions,
- These tools are specific for each installation,
  ESTEC: HYDRA, QUAD, DUAL 320kN, 160/80kN single axis shaker, …
- Identify critical aspects: facility performance issues and frequency shifts.
- Better assessment of all notching profiles since the very first run.
- Optimisation of test execution parameters, e.g. control parameters.



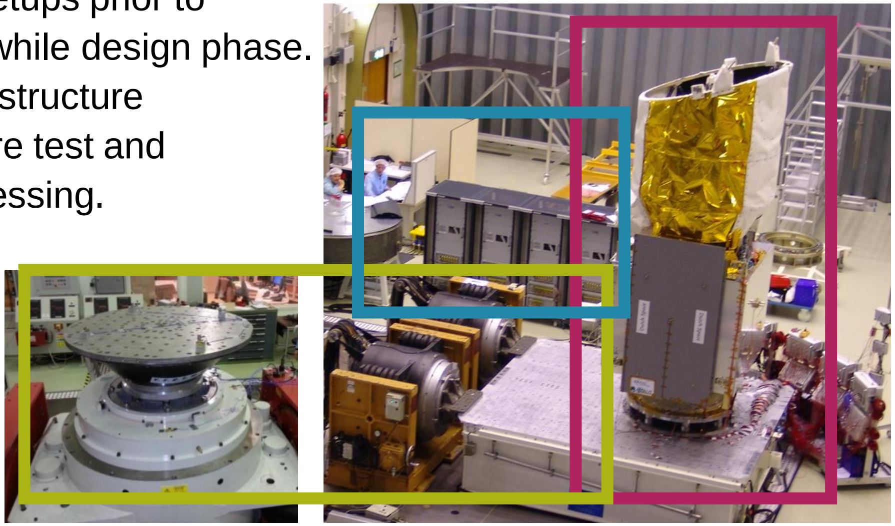
NASA, NASA-HDBK-7008, *www.nasa.gov*

In general: Numerical prediction of a spacecraft vibration test:

- Predict dynamic characteristic of complex test setups prior to test, before arrival of the S/C at the test facility, while design phase.
- To avoid over- and undertesting, damage of the structure
- To increase the quality and efficiency of the entire test and correlation of mathematical models in post-processing.

Coupled dynamic system comprising:

1. **Excitation system (Shaker),**
2. **Vibration control system,**
3. **Spacecraft (S/C) or structure being tested including all test brackets and adapters.**



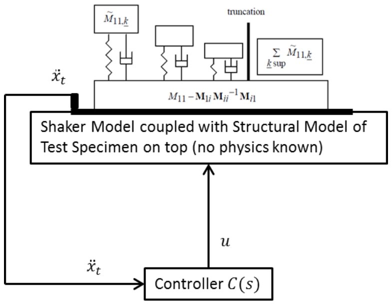
European Space Agency (ESA), *www.esa.int*

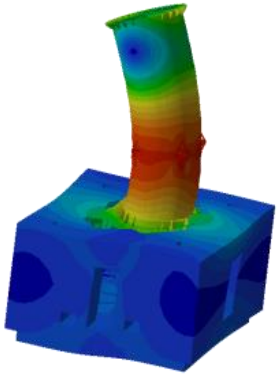
Sine Control Test Prediction

Statement

Based on experimental test data ($FRF(i\omega) = \frac{\ddot{x}(i\omega)}{u(i\omega)}$) the outcome of a real experimental sine control test can be numerically predicted and re-calculated!

- Numerical (FE, multi-physical, multi-body) substructure models (shaker, test specimen) are usually not a priori available or accessible.
- Relatively fast and reliable methodology for numerical test prediction.
- No assumptions on the connections between different substructures need to be made.
  - Structural coupling between several test specimen/structure models,
  - Physical coupling of mechanical and electrical shaker models with the entire test specimen model.





FEM interaction of dummy satellite and QHE
M. Appolloni, ESA-ESTEC, 2007

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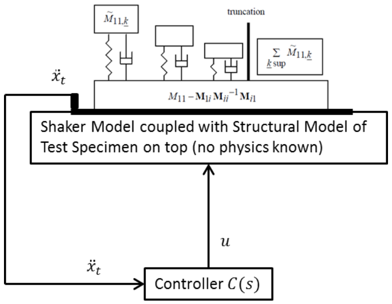
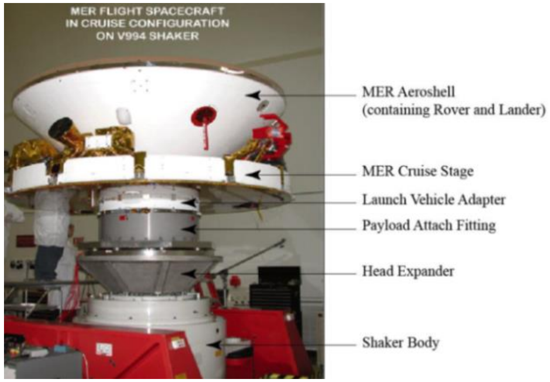
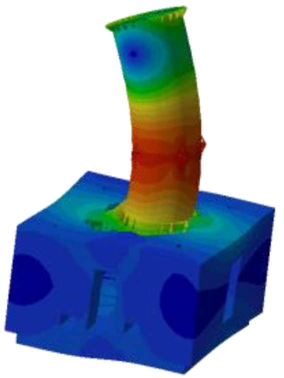


Requirements

- The test setup needs to be physically or numerically available and mounted or coupled to the vibration testing facility.
- All numerical test predictions are linear.



NASA, NASA-HDBK-7008
www.nasa.gov



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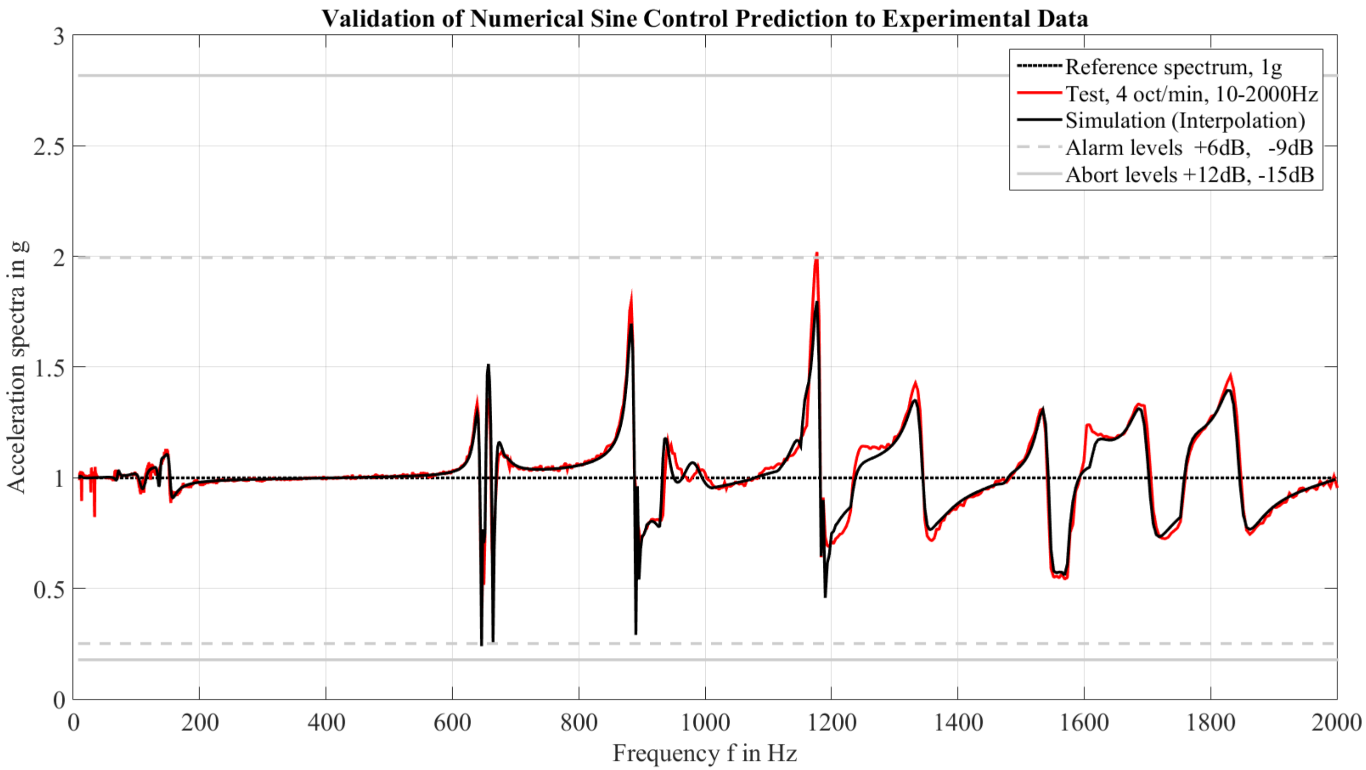

Sine Control Test Prediction

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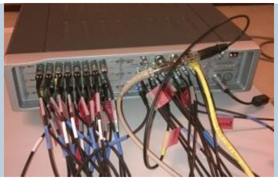
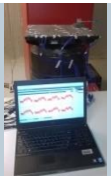
Procedure

- **Prepare** test setup and sensor instrumentation
- Perform **system identification**
  - Low level test runs, e.g. open-loop random, self-check data

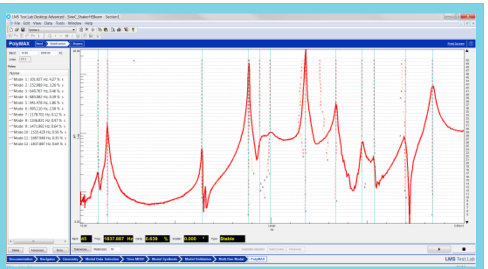




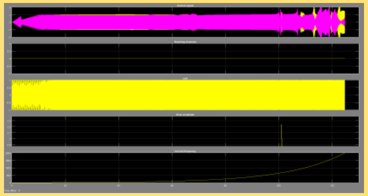
- **Calculate** $FRF(i\omega) = \frac{\ddot{x}(i\omega)}{u(i\omega)}$ from experimental test data
- Derive **dynamical models**
  - Estimate modal model, e.g. Polymax
  - Derive models, e.g. polynomial transfer function or state-space models
  - Discretise models – necessary step for closed-loop sine control simulation!

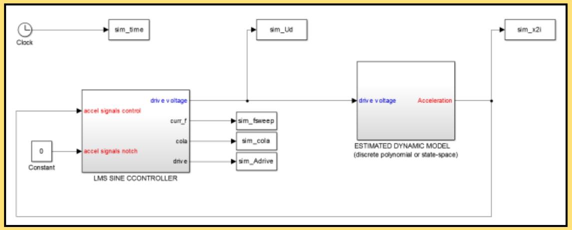
$$x_{k+1} = Ax_k + Bf_k$$
$$y_k = Cx_k + Df_k$$

$$H(s) = \frac{\ddot{x}(s)}{F(s)} = \frac{LR}{s^2} + \sum_{i=1}^{n} \frac{\psi_i \cdot l_i^T}{s-\lambda_i} + \frac{\psi_i^* \cdot l_i^H}{s-\lambda_i^*} + UR$$

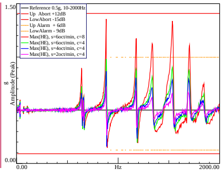
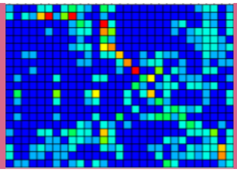


- Load discretised dynamical models in sine control simulation
- **Define** sine **control** and **simulation parameter**
  - Frequency band,
  - Sweep rate (log/linear, up/down),
  - Compression factor and number of periods
- **Run simulation**





- **Validation** of simulation results to experimental data (if applicable)
  - Time domain, e.g. acceleration and drive voltage time series
  - Frequency domain, e.g spectra and FRFs

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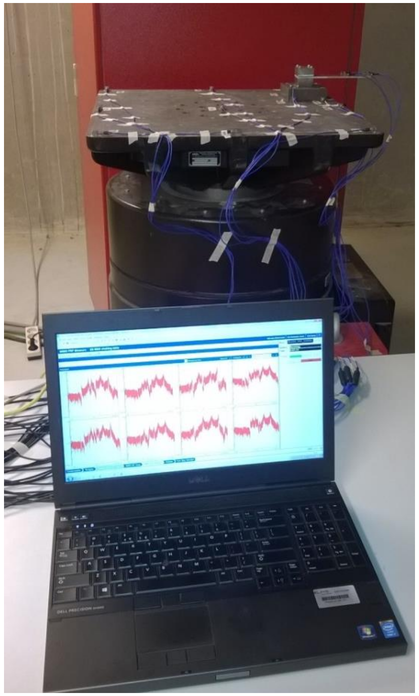
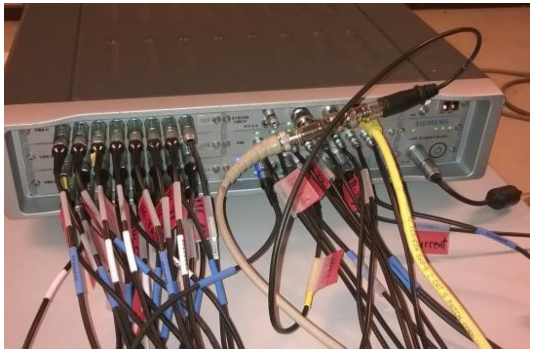
Sine Control Test Prediction

Test Setup Preparation

- System identification
  - Impact testing of structural models coupled to shaker table in fixed-free boundary conditions
  - Open-loop random testing $G_{Shaker+S/C}(i\omega) = \frac{\ddot{x}_t(i\omega)}{U(i\omega)} \rightarrow \tilde{G}_{Shaker+S/C}(i\omega)$
- Validation test cases:
  - Closed-loop sine control testing for validation testing
  - Different control parameter settings
- Measurement sensors:
  - Control and monitor signals: acceleration sensors, equal sensor setup as for modal analysis in free-free
  - Drive signals: SCADAS output voltage and shaker current

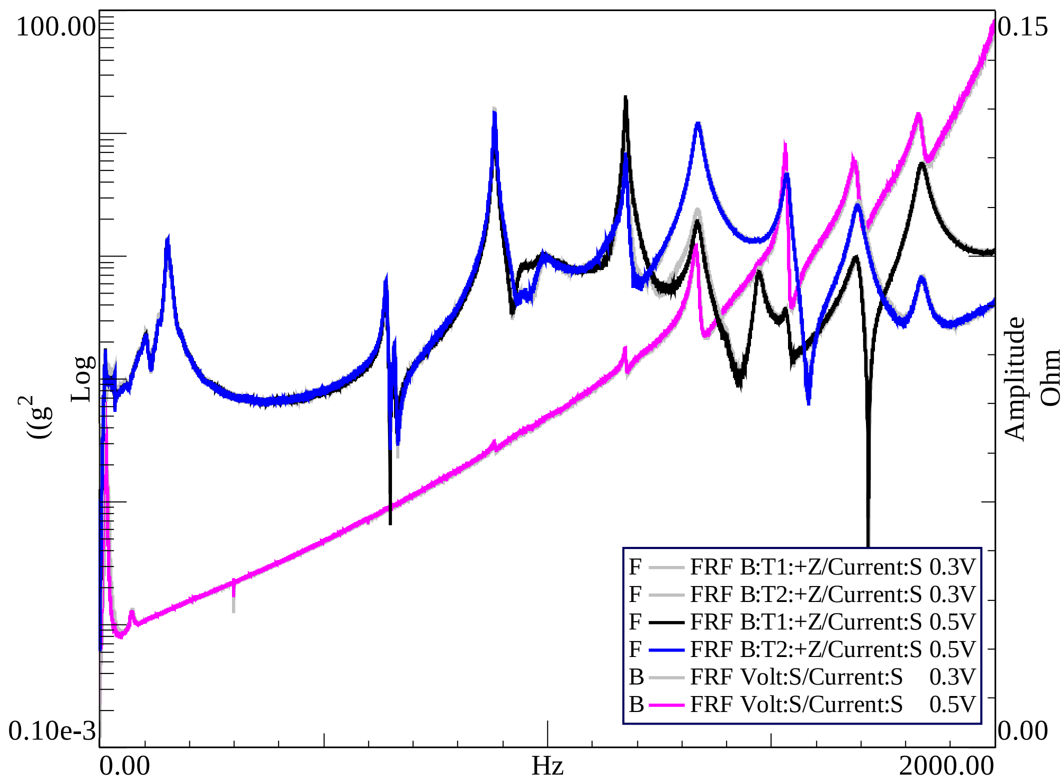


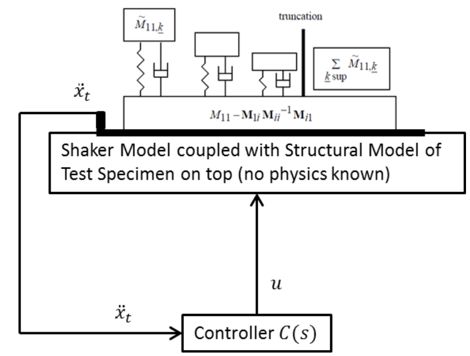


Sine Control Test Prediction

System Identification Step

- Use data from open loop random testing
- Use of self-check data for further test predictions
- Linearity analysis: 2 input voltage levels 0.3 and 0.5V





Drive voltage

B:T2 B:T1

- → Less noisy characteristic
- → No change with different levels
- → Only on suspension mode
  - → Softening effect

Sine Control Test Prediction

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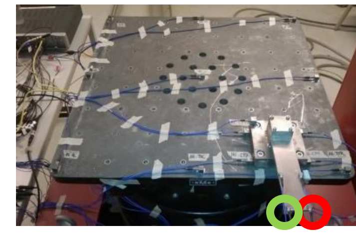
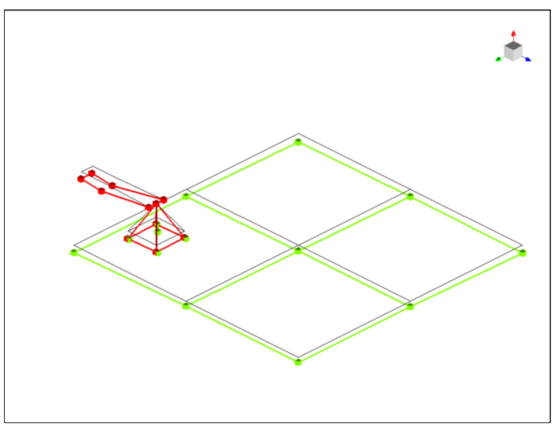
System Identification Step

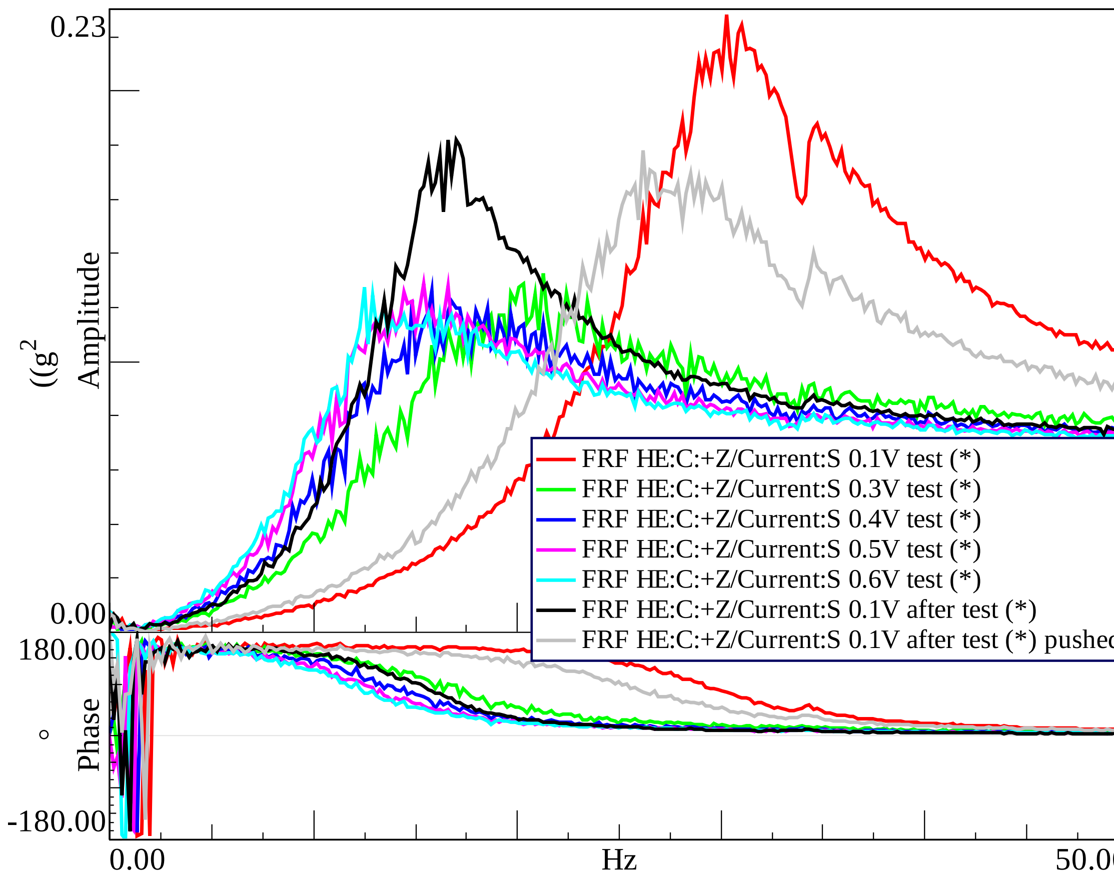
- Linearity analysis: suspension mode

Run	Natural Freq. (Hz)	Damping ratio (%)
0.1	29.44	15.78
*0.2**	*13.96*	*20.99*
0.3	16.22	27.22
0.4	13.64	26.66
0.5	12.59	25.92
0.6	12.13	27.18
*0.1**	*15.44*	*18.24*
*0.1***	*25.65*	*20.48*

* After test
** After test, pushed







Sine Control Test Prediction

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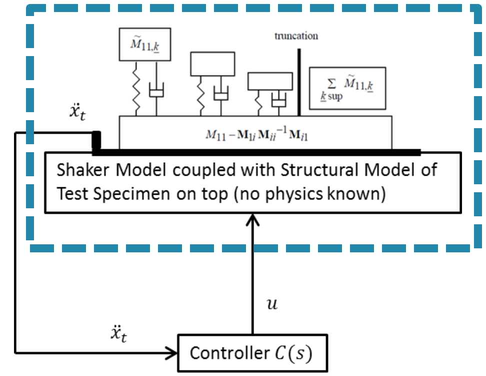
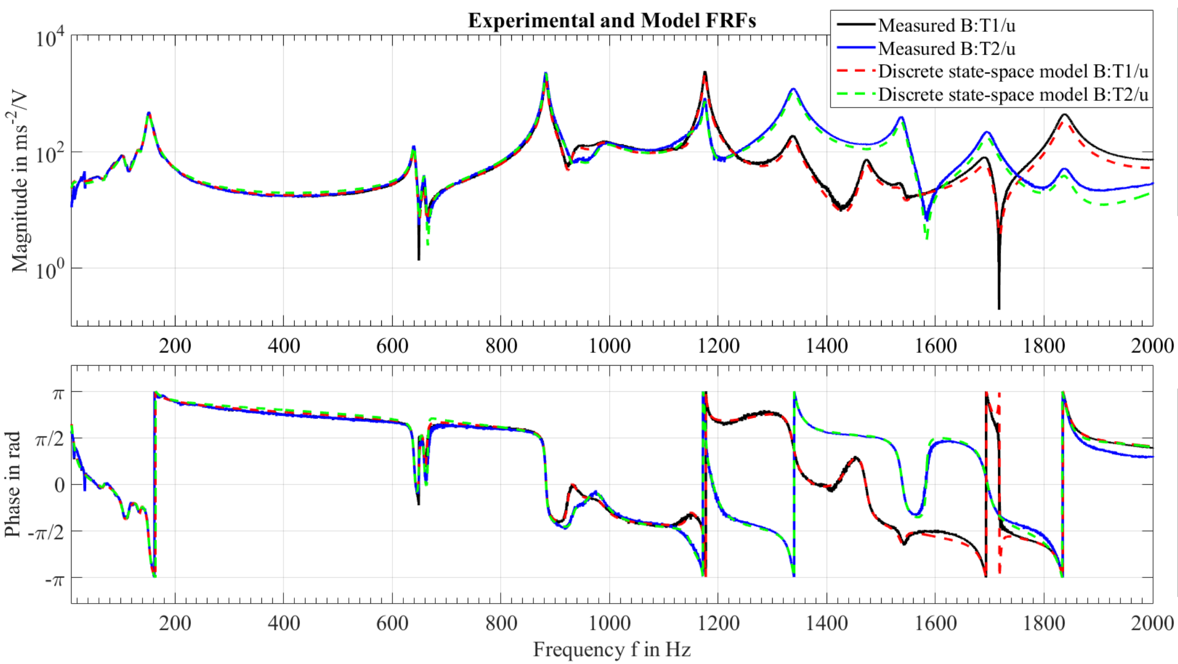
Derivation discrete dynamical modal models (SIMO)

- Calculate $FRF(i\omega) = \dfrac{\ddot{x}(i\omega)}{u(i\omega)}$ from experimental test data
- Derive dynamical models
  - Estimate modal model, e.g. Polymax: good fit, stable and physical poles
  - Derive models, e.g. polynomial transfer function or state-space models
  - Discretise models





$$H(s) = \frac{\ddot{x}(s)}{u(s)} = LRs^2 + \sum_{i=1}^{n} \frac{\psi_i \cdot l_i^T}{s-\lambda_i} + \frac{\psi_i^* \cdot l_i^H}{s-\lambda_i^*} + UR$$

Model Conversion →

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

Discretisation

Model Conversion

$$\begin{aligned} x_{k+1} &= A'x_k + B'u_k \\ y_k &= C'x_k + D'u_k \end{aligned}$$

(alternative)

$$H_i(z) = \frac{\ddot{X}(z)}{u(z)} = \frac{b_o + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}{1 + a_1 z^{-1} + \ldots + a_{2n} z^{-2n}}$$

Sine Control Test Prediction

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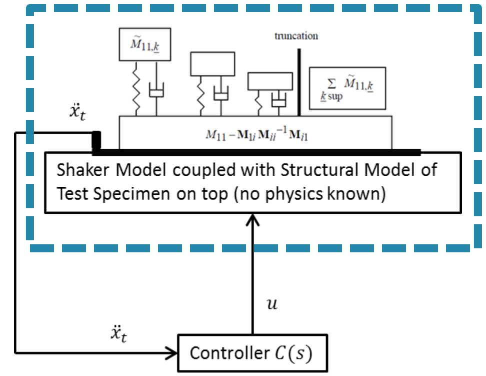

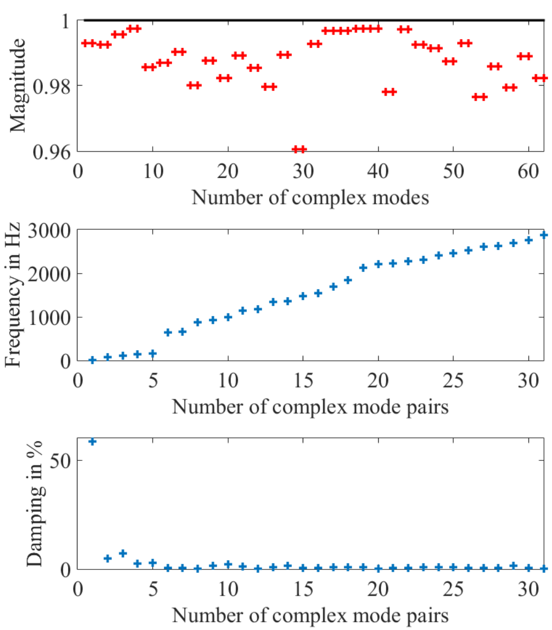

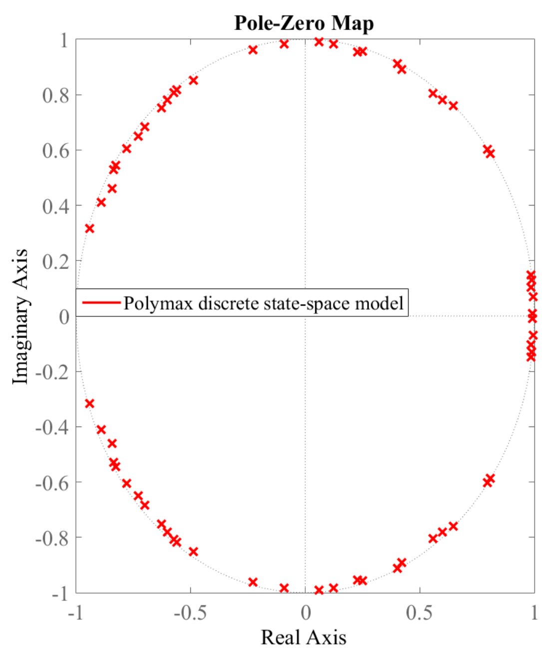

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Model Conversion →

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}u$$
$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}u$$

Discretisation

$$\boldsymbol{x}_{k+1} = \boldsymbol{A}'\boldsymbol{x}_k + \boldsymbol{B}'u_k$$
$$\boldsymbol{y}_k = \boldsymbol{C}'\boldsymbol{x}_k + \boldsymbol{D}'u_k$$

Model Conversion (alternative)

$$\boldsymbol{H_i}(z) = \frac{\ddot{X}(z)}{u(z)} = \frac{b_o + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}{1 + a_1 z^{-1} + \ldots + a_{2n} z^{-2n}}$$

Sine Control Test Prediction

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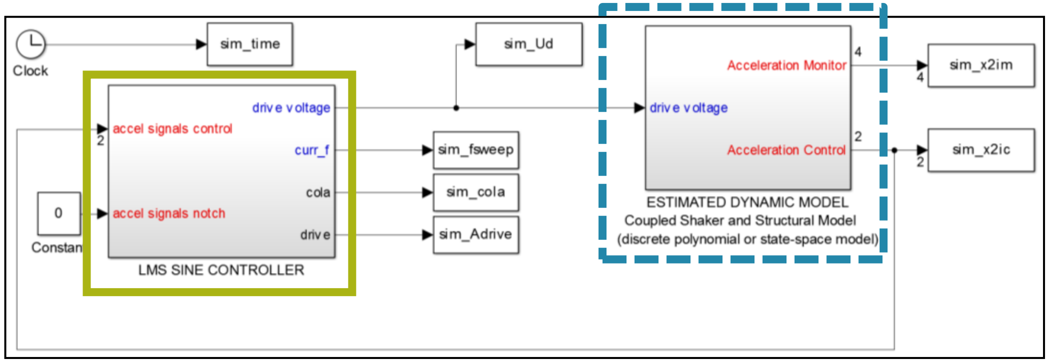
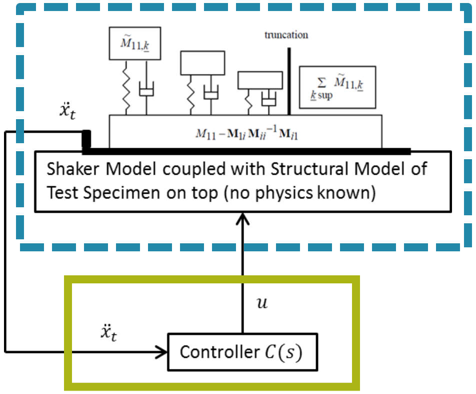
Simulation (SIMO)

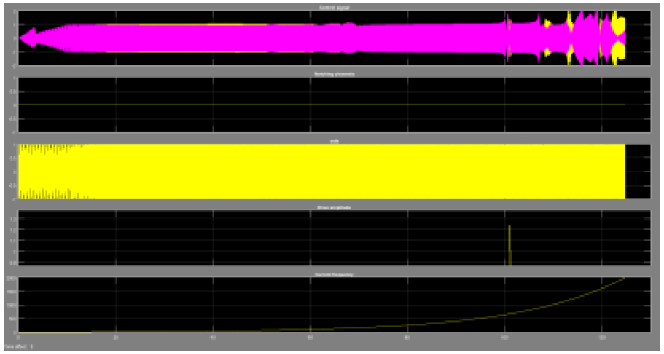
- Load discretised dynamical models in sine control simulation
- Define sine control and simulation parameter
  - Frequency band,
  - Sweep rate (log/linear, up/down),
  - Compression factor and number of periods





$$
\begin{aligned}
x_{k+1} &= A' x_k + B' u_k \\
y_k &= C' x_k + D' u_k
\end{aligned}
$$

- Run simulation



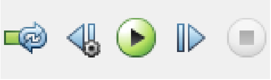
Control channel (T1, T2)

Notch channels (not defined)

Cola signal

Drive voltage amplitude

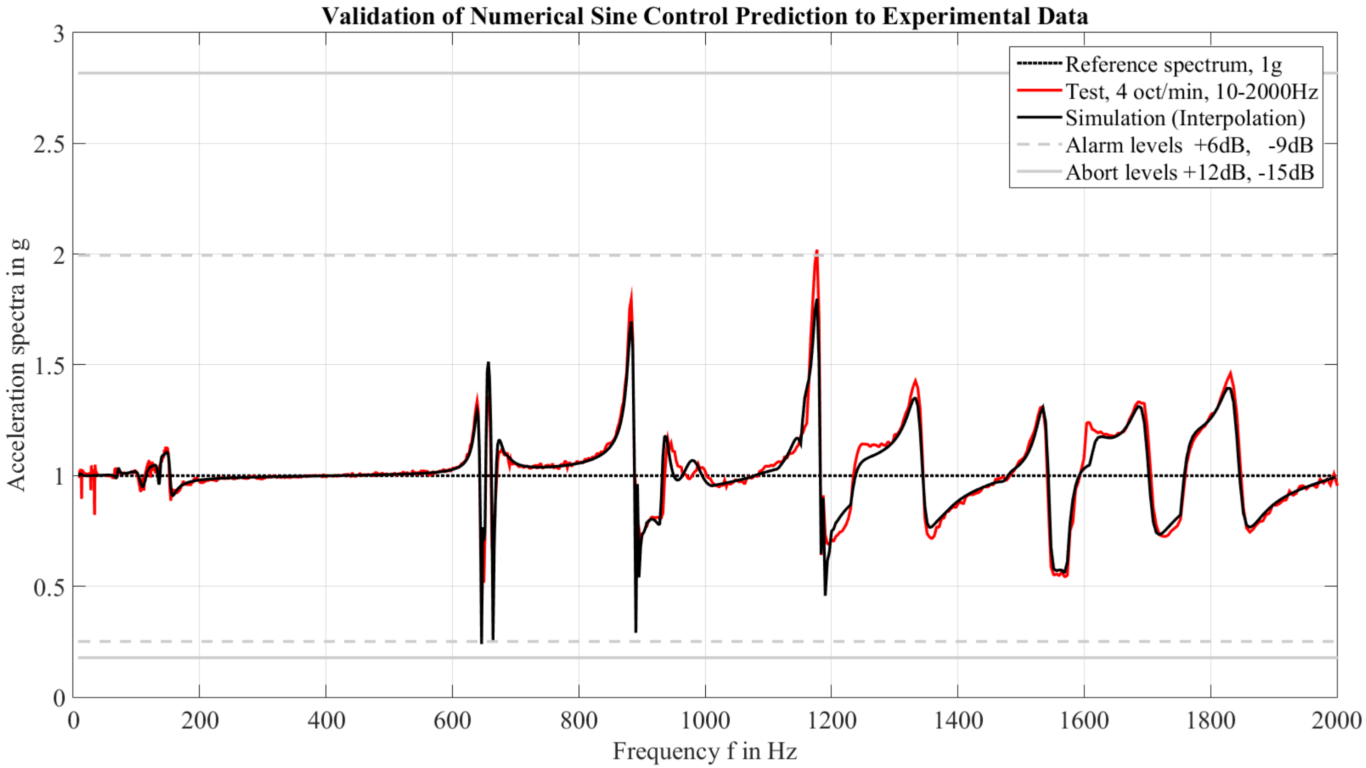
Sweep frequency (log)



Sine Control Test Prediction

Validation of simulation results to experimental data

- Sine control test, max. control of beam sensors B:T1 and B:T2
- 1g, 10-2000Hz, 4oct/min, c=4



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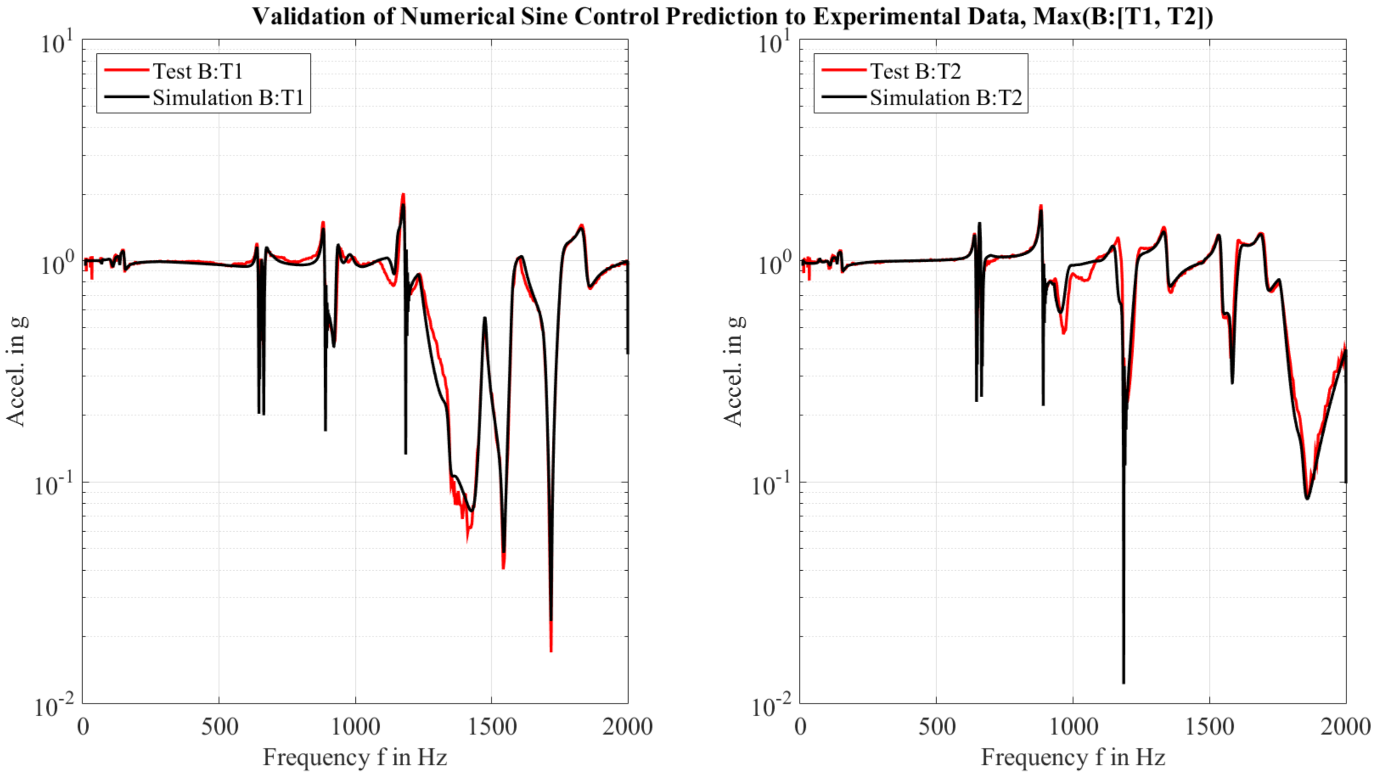

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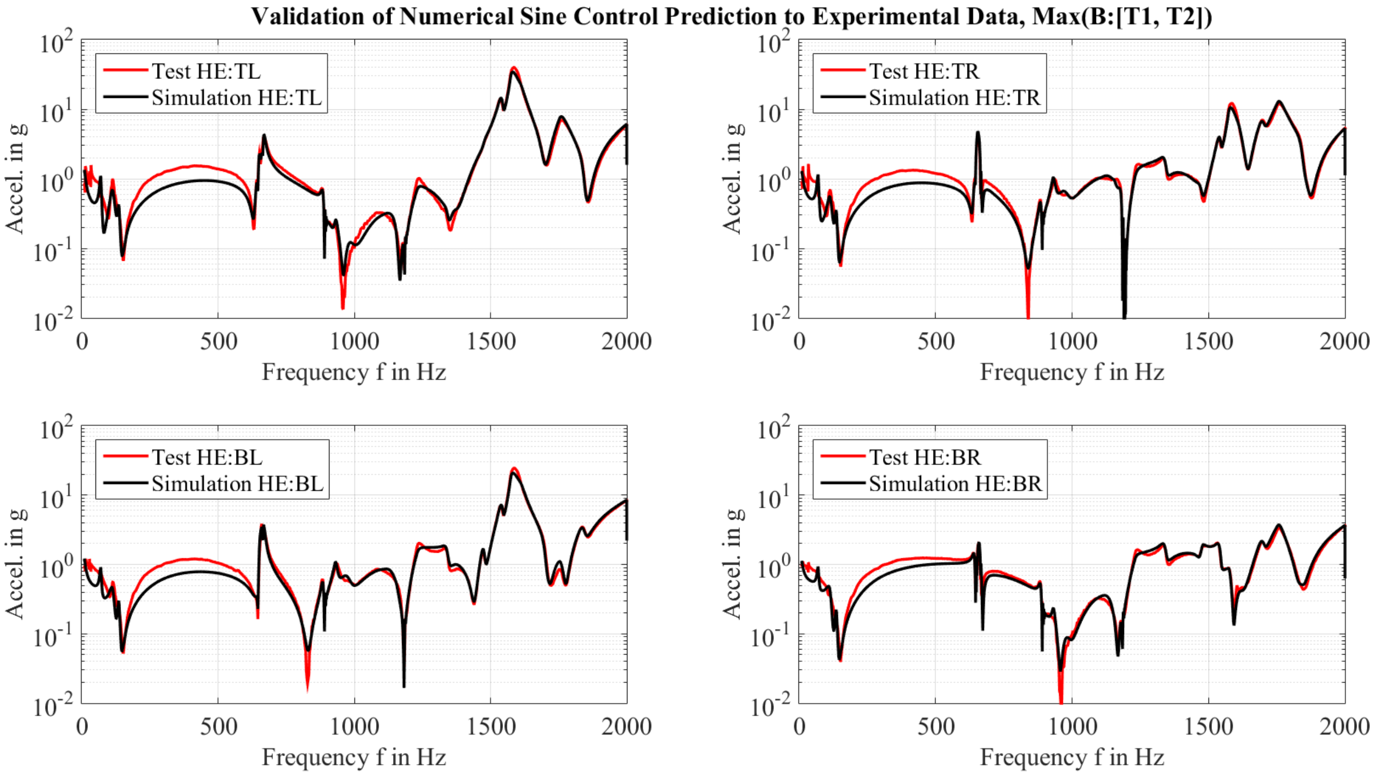

Sine Control Test Prediction

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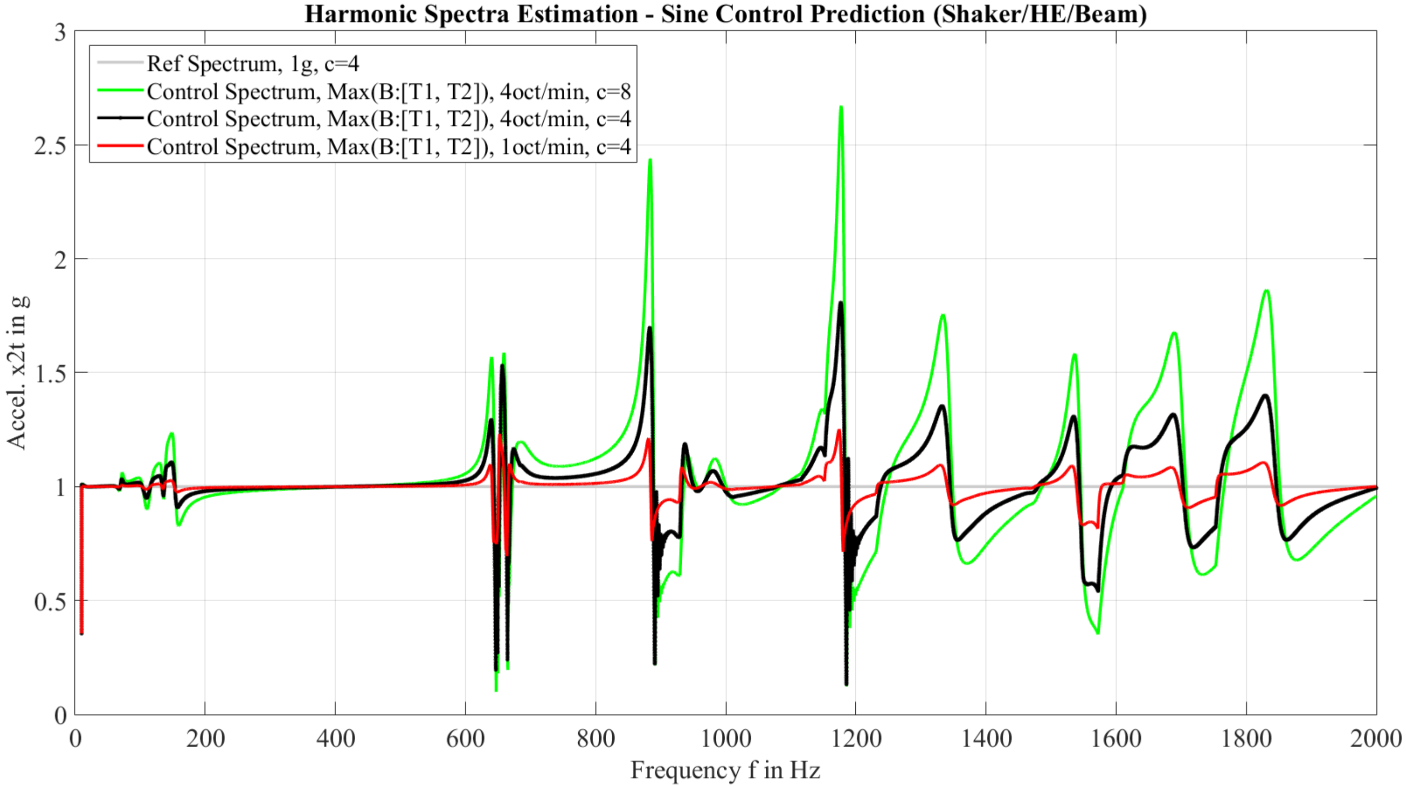
Further possibility of virtual sine control prediction

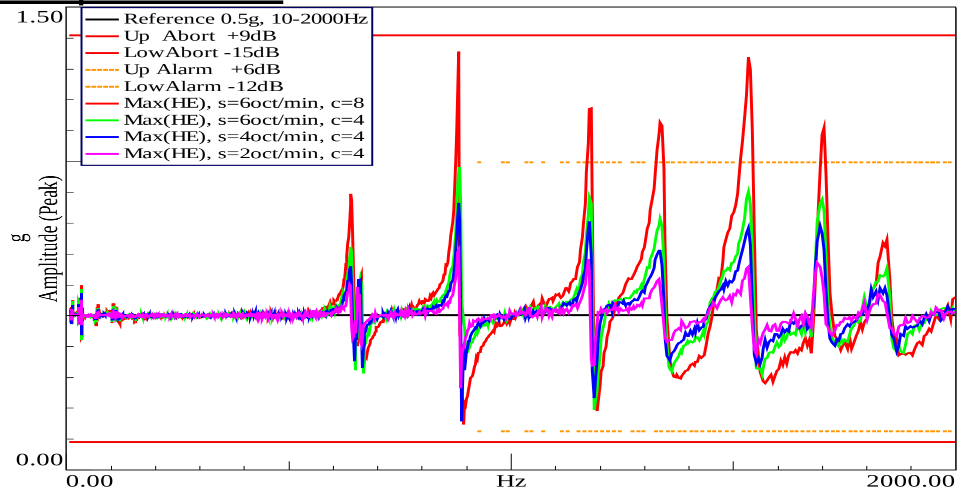
- Adapt control parameter to minimise occurrence of beating
  - Sweep rate → low: better control, less deviation, reduced beating effect (black/red)
  - Compression factor → low: faster control, less deviation, increased beating (black/green)



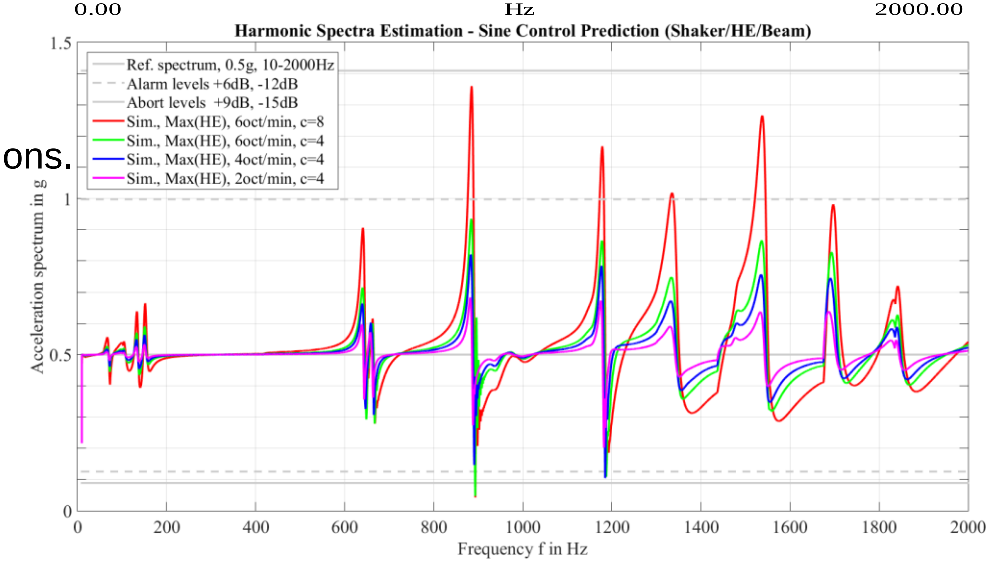
Sine Control Test Prediction

Further possibility of virtual sine control prediction

- **Test: Sine Control**
  - Control (max) on HE sensors HE:BL, HE:BR, HE:TL, HE:TR
  - Monitor beam sensors B:T1 and B:T2
  - Sine control with 0.5g, 10-2000Hz and different sweep rate and compression factors



- **Simulation: Sine Control Prediction**
  - Note: low frequency deviations for frequencies f<600Hz due to model deviations.
- Validation
  - Qualitatively same trend and influence of control parameter settings.
    - Low sweep rate → better control, decreased beating
    - Low compression factor → better control, increased beating



Sine Control Test Prediction

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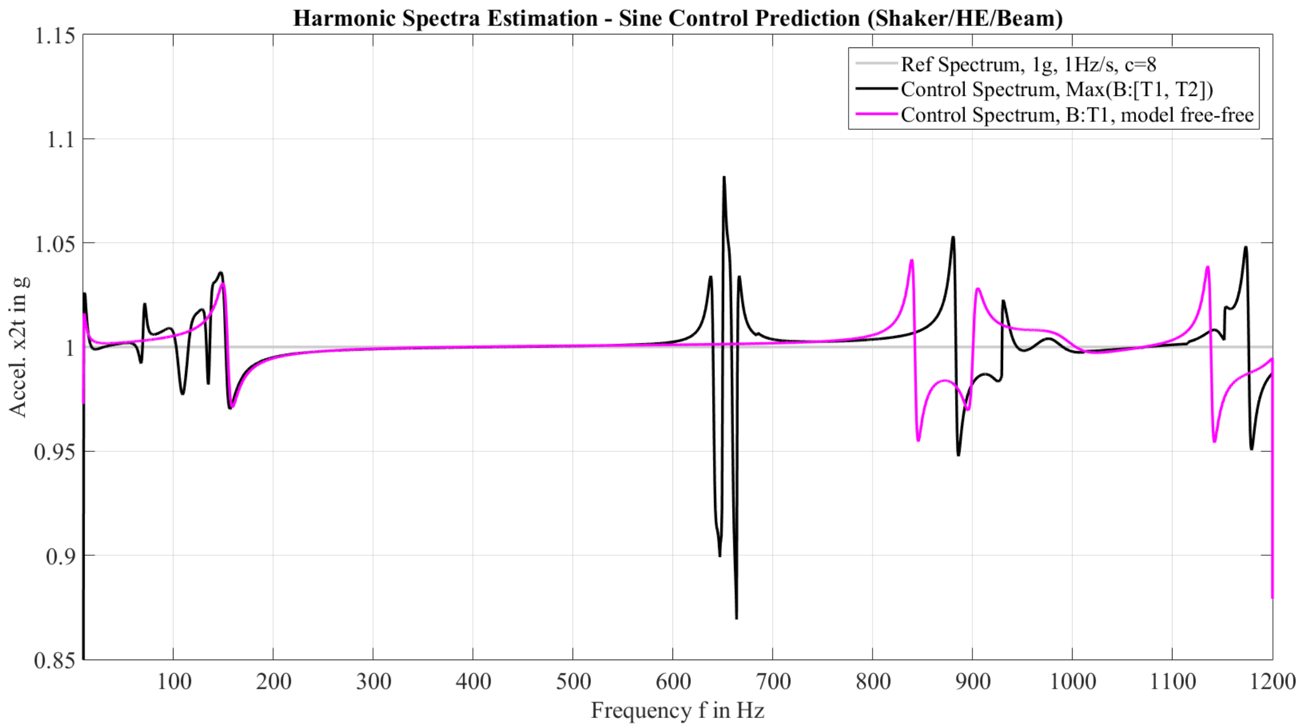
The importance of boundary conditions and coupling effects (shaker/structure)

- Virtual shaker testing test prediction under
  - **fixed-free** boundary conditions with
  - **coupled shaker/structure** dynamics.
- Industrial practice: S/C test simulation:
  - **fixed-free** boundary conditions on FEM
  - and application of **ground base acceleration**
    → No coupled shaker/structure dynamics
    → shift of resonance frequencies (test/sim)



Sine Control Test Prediction

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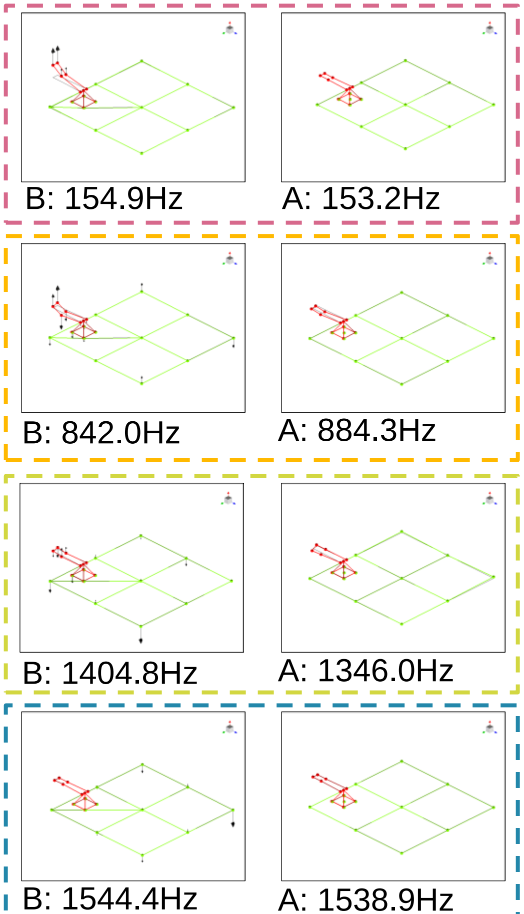
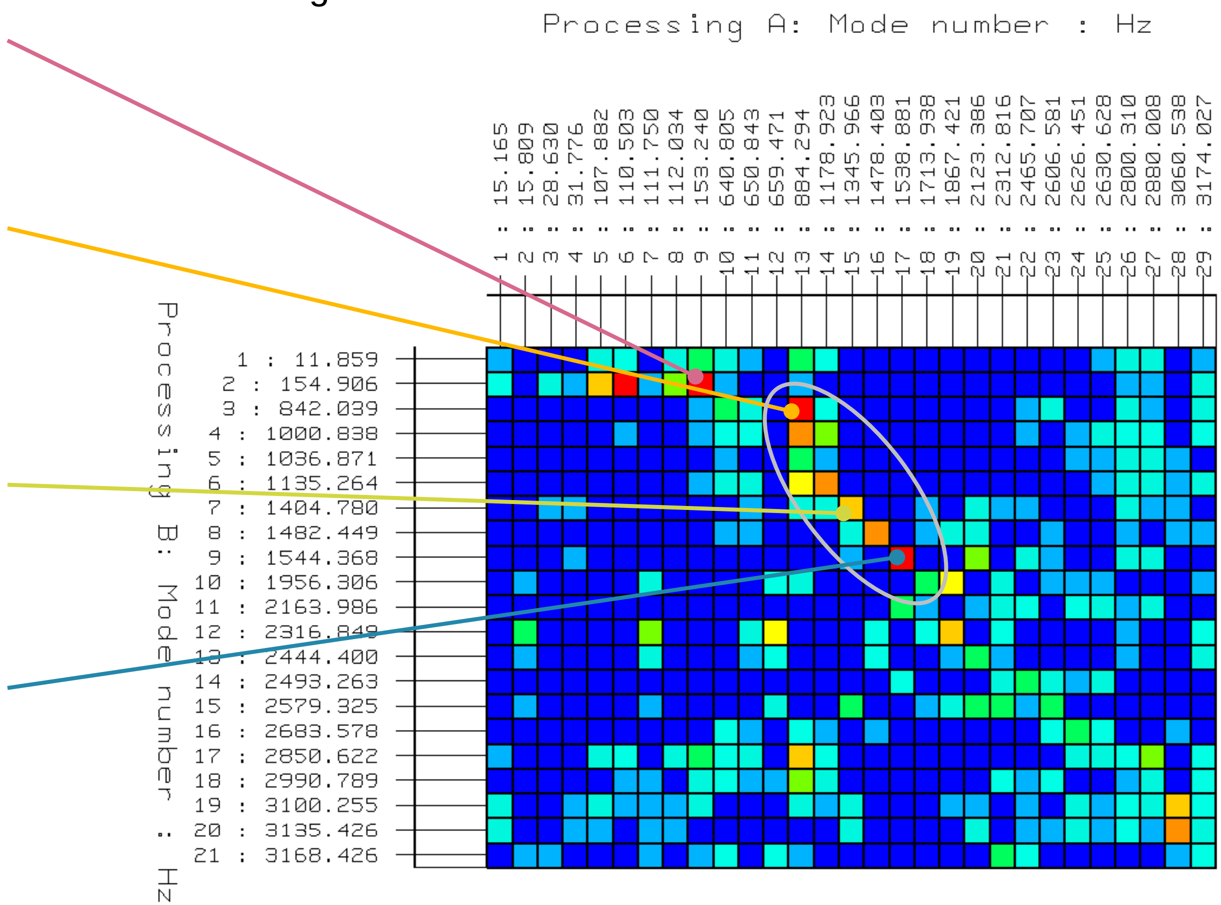
The importance of boundary conditions and coupling effects (shaker/structure)

- **HE/Beam** in **free-free** and **fixed-free** on shaker: **Impact Testing**



- MAC Processing A: fixed-free
- MAC Processing B: free-free



Summary and Future Work

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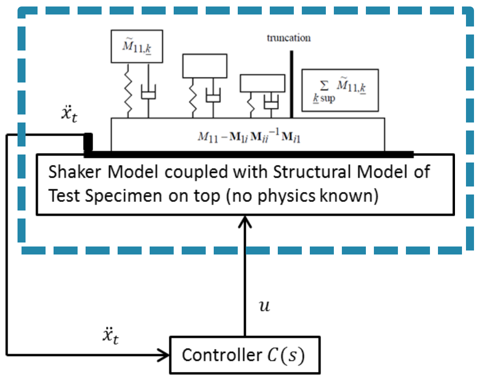
Summary and Conclusions

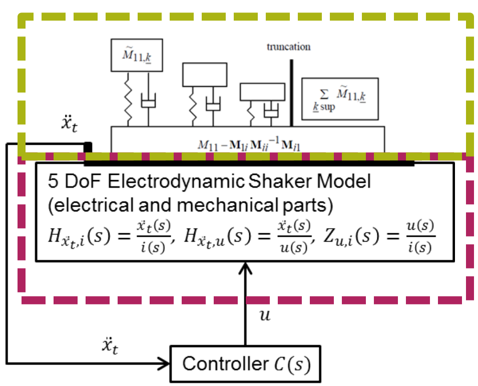
- Based on experimental test data the outcome of a real experimental sine control test can be numerically predicted and re-calculated!
- Numerical test predictions show good agreement to experimental test cases for validation → deviations at peaks induced by discretisation.
- Simulation environment is used to highlight the effect of beating and how it can be minimised by adapting control parameter.
- The importance of the boundary conditions and coupling effects is assessed by using dynamical models representing the test specimen in free-free and fixed-free boundary conditions.



Future work

- Enhance data driven modelling and simulation approach for all measurement channels comprising HE sensors as it is industrial practice.
- Apply enhanced modal parameter estimation algorithms, e.g. MLMM in simulation methodology.
- Continuation on physical modelling of lumped-parameter physical models coupled to test specimen structural models
- Enhance vibration control algorithms, e.g. pre-shaping of shaker drives

Interface modelling shaker+structure



Thank you for your attention!

Questions?

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Backup Slides

Sine Control Test Prediction

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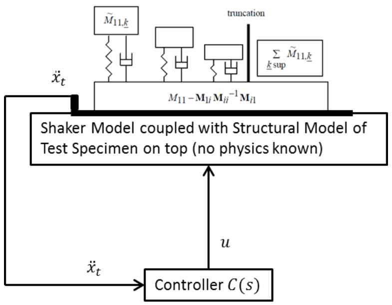
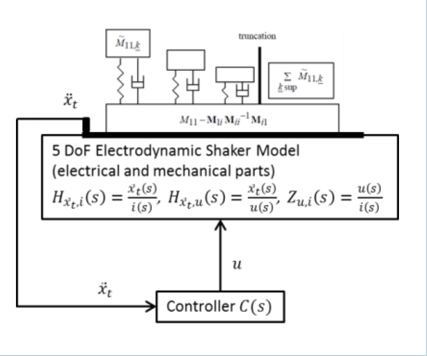
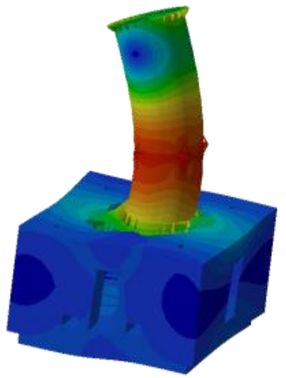
Statement

Based on experimental test data ($FRF(i\omega) = \frac{\ddot{x}(i\omega)}{u(i\omega)}$) the outcome of a real experimental sine control test can be numerically predicted and re-calculated!

- Numerical (FE, multi-physical, multi-body) substructure models (shaker, test specimen) are usually not a priori available or accessible.
- Relatively fast and reliable methodology for numerical test prediction.
- No assumptions on the connections between different substructures need to be made.
  - Structural coupling between several test specimen/structure models,
  - Physical coupling of mechanical and electrical shaker models with the entire test specimen model.
    → *under research!*
    → *not part of this presentation!*
    - *Derivation of lumped parameter electro-dynamic shaker models (with sufficient DoFs ?),*
    - *Derivation of structural test specimen models,*
    - *Coupling in virtual simulation environment with vibration controller for numerical test predictions!*







FEM interaction of dummy satellite and QHE
M. Appolloni, ESA-ESTEC, 2007

Sine Control Test Prediction

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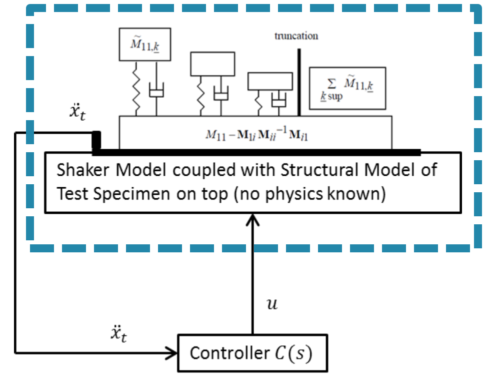
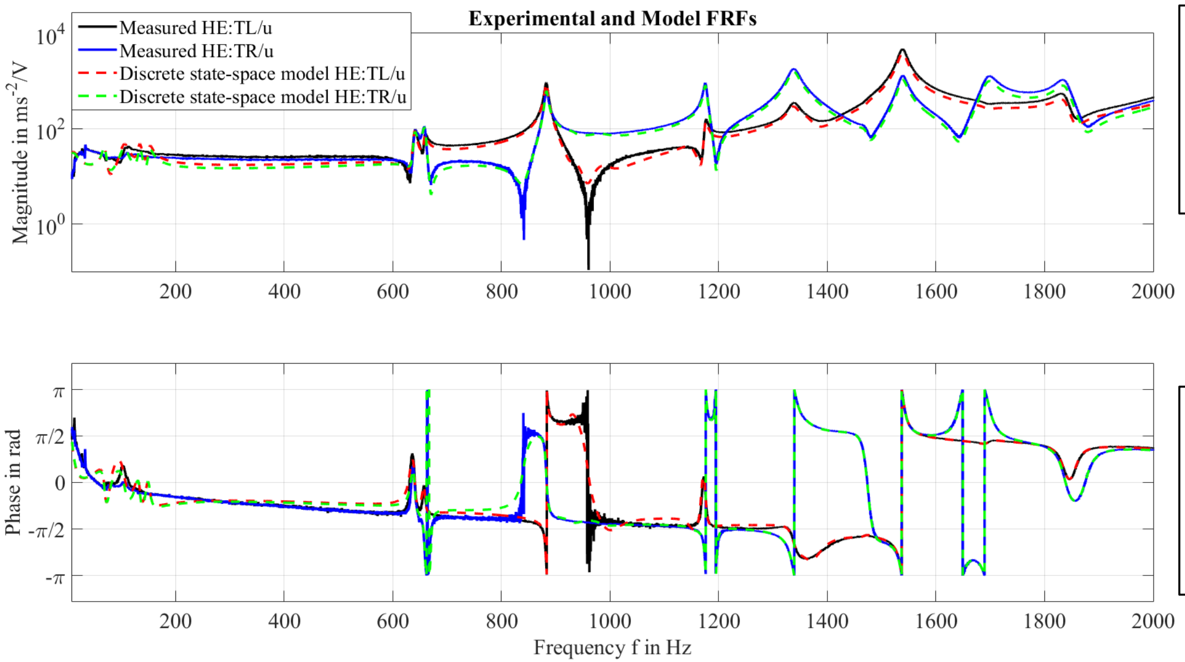
Derivation discrete dynamical modal models (SIMO)

- Calculate $FRF(i\omega) = \frac{\ddot{x}(i\omega)}{u(i\omega)}$ from experimental test data
- Derive dynamical models
  - Estimate modal model, e.g. Polymax: good fit, stable and physical poles
  - Derive models, e.g. polynomial transfer function or state-space models
  - Discretise models





$$H(s) = \frac{\ddot{x}(s)}{u(s)} = LRs^2 + \sum_{i=1}^{n} \frac{\boldsymbol{\psi}_i \cdot \boldsymbol{l}_i^T}{s-\lambda_i} + \frac{\boldsymbol{\psi}_i^* \cdot \boldsymbol{l}_i^H}{s-\lambda_i^*} + UR$$

Model Conversion →

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}u \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}u \end{aligned}$$

Discretisation

Model Conversion (alternative)

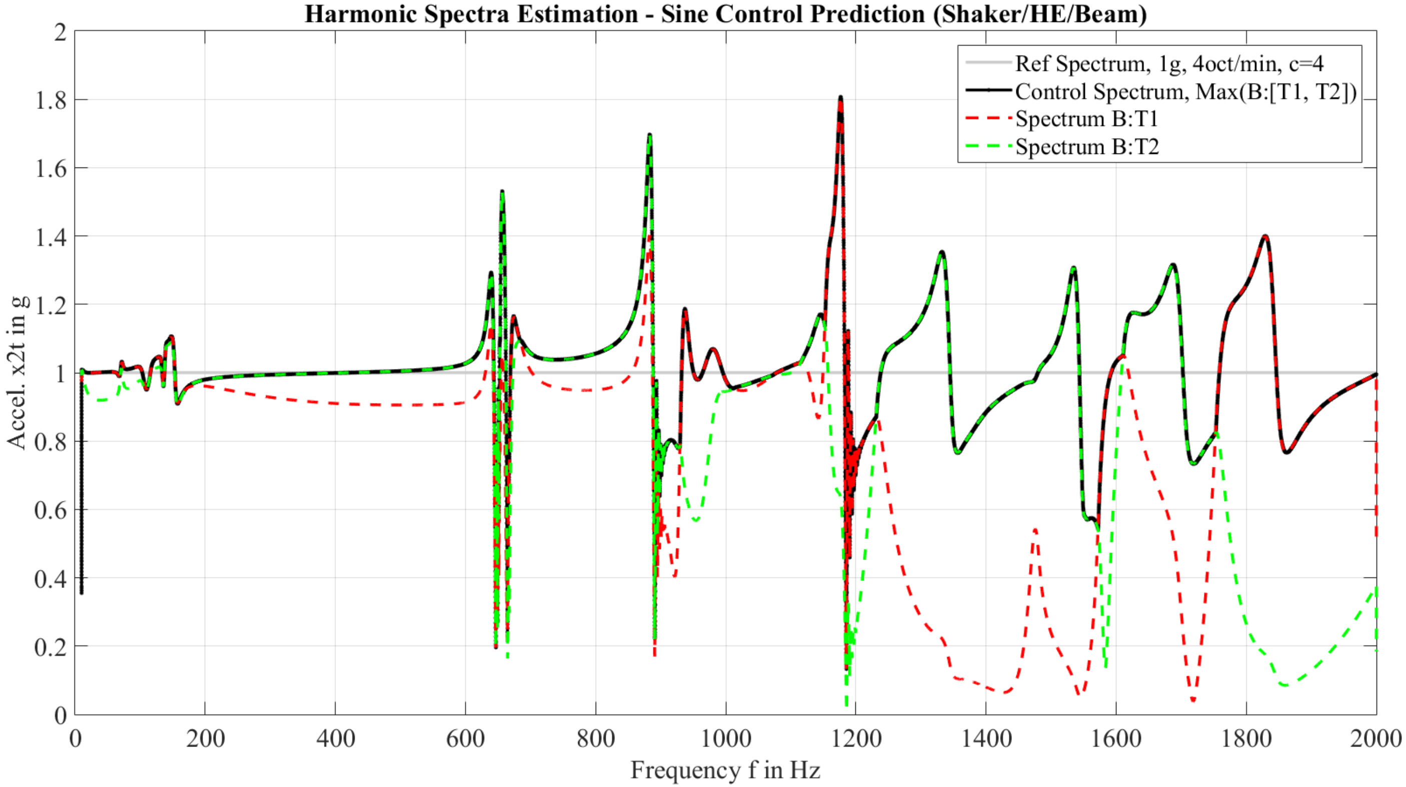
$$\begin{aligned} \boldsymbol{x}_{k+1} &= \boldsymbol{A}'\boldsymbol{x}_k + \boldsymbol{B}'u_k \\ \boldsymbol{y}_k &= \boldsymbol{C}'\boldsymbol{x}_k + \boldsymbol{D}'u_k \end{aligned}$$

$$\boldsymbol{H_i}(z) = \frac{\ddot{X}(z)}{u(z)} = \frac{b_o + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}{1 + a_1 z^{-1} + \ldots + a_{2n} z^{-2n}}$$

Sine Control Test Prediction

Simulation results and control principle of maximum control

- Sine control test, max. control of beam sensors B:T1 and B:T2
- 1g, 10-2000Hz, 4oct/min, c=4



Sine Control Test Prediction

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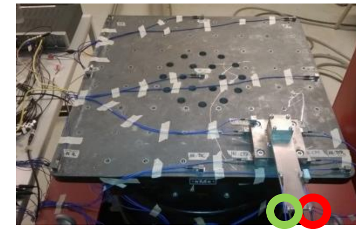
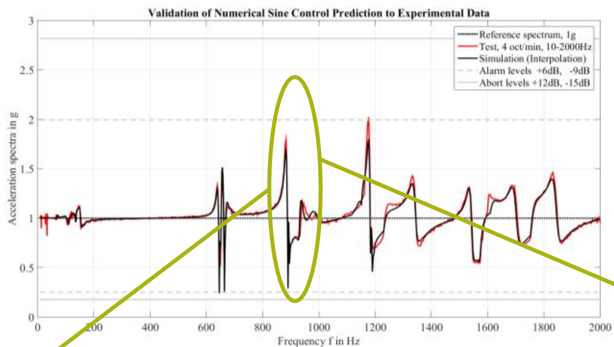
Validation of simulation results to experimental data

- Sine control test, max. control of beam sensors B:T1 and B:T2
- 1g, 10-2000Hz, 4oct/min, c=4





- Deviation in control spectra between sine control **test results** and **numerical prediction** correlated to
- Deviation in discrete state-space model (dashed red) used in simulation to **measured** and **synthesised** open-loop random FRF.

Factor ≈ 1.059

Factor ≈ 1.065