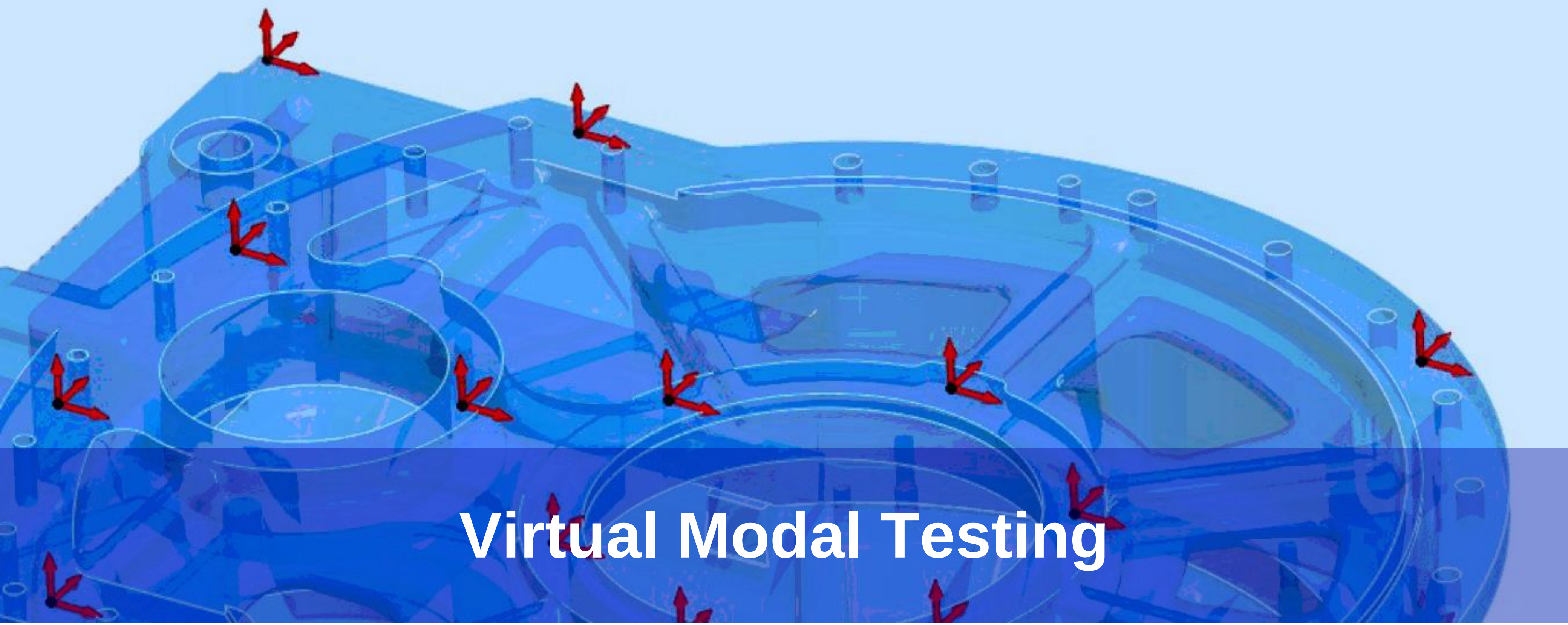


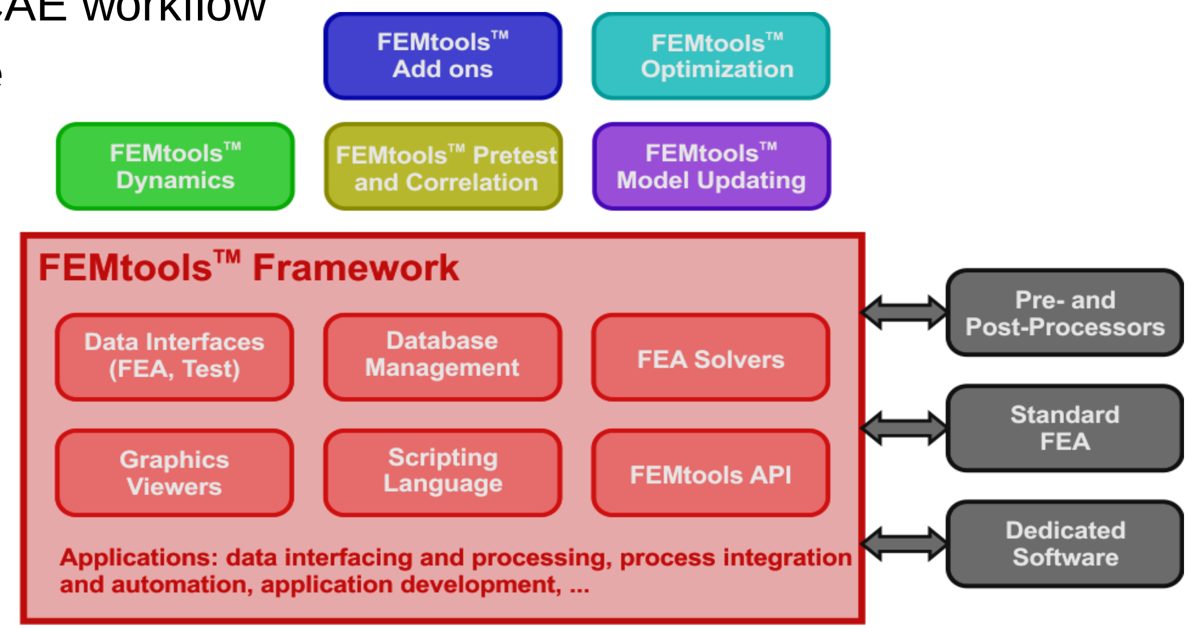
Virtual Modal Testing

E. Dascotte
Dynamic Design Solutions (DDS) NV

IMAC XLII
Orlando, FL
Jan 30, 2024

Dynamic Design Solutions

- CAE software development and services
- Specializing in structural dynamics, integration of FEA with testing, validation and updating of finite element models
- Main product is “FEMtools”
  - Multi-functional, cross-platform and solver-independent CAE software suite providing analysis and scripting solutions
  - Neutral, open database combining FE and test data
  - Easy integration in any CAE workflow
  - Customizable, extensible



FEMtools
simulate > validate > update > optimize

Overview of Tools

FEMtools

Model Updating
- Response Selections
- Parameter Selection
- Parameter Relations
- Differential Sensitivities
- Finite Difference Sensitivities
- Parameter Updating
- Force Identification
- Probabilistic Analysis

Add-Ons
- Data Acquisition for NI (DAQ-NI)
- Rigid Body Properties Extractor
- Modal Parameter Extractor (MPE)

Optimization
- Single and Multi-Objective
- Support of Large Number of Parameters
- Mesh Morphing for Shape Optimization
- Gradient-Based Optimizer
- Topology and Topometry Optimization
- Response Surface Modeling
- Probabilistic Analysis

Interface and Drivers
- ABAQUS
- ANSYS
- LS-DYNA
- NASTRAN, OPTISTRUCT
- SAP2000
- UNIVERSAL FILE

Correlation Analysis
- Spatial Correlation (FE-Test)
- Expansion and Reduction
- Smoothing, Normalization, Re-scaling
- Global Shape Correlation
- Local Shape Correlation
- FRF Correlation

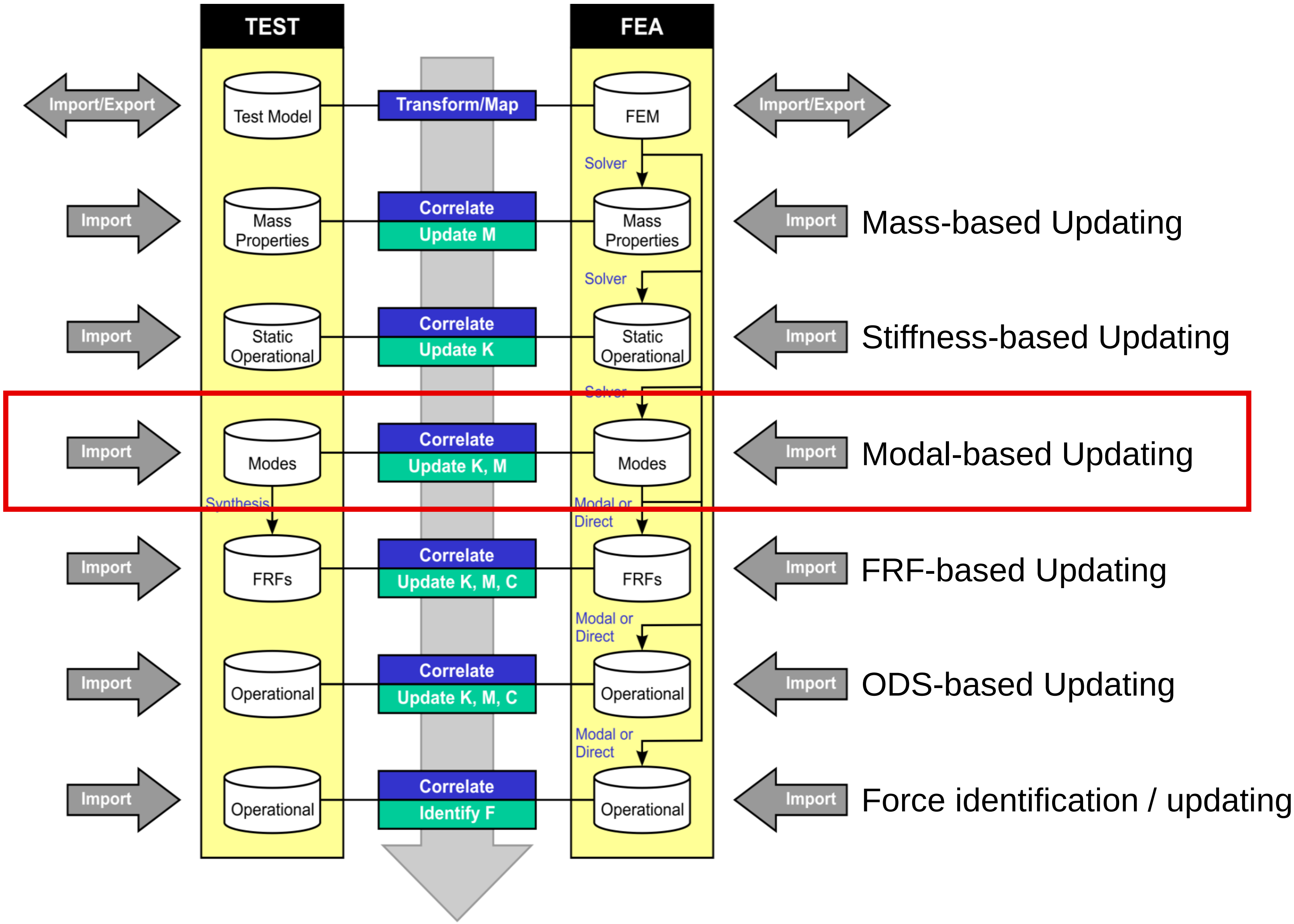
Pretest Analysis
- Target Modes Selection
- Sensor, Exciter and Support Selection
- Test Model Generation

Dynamics (Simulation)
- Frequency Response Analysis
- Modal-based Assembly (MBA)
- FRF-based Assembly (FBA)
- Modal Sensitivity
- Superelements Analysis
- Variational Analysis
- Time Domain Simulation (TDS)

Framework
- User Interface, Graphics Viewer
- Commands
- Database Management
- FEMtools Script
- FEMtools API
- Mesh Tools
- Finite Element Matrices Library
- Mass Analysis
- Signal Processing (DSP)

Basic FEA Solvers
- Static
- Modal
- Stress and Strain

FE Model Validation and Updating Types



Sources of Uncertainties and Variability

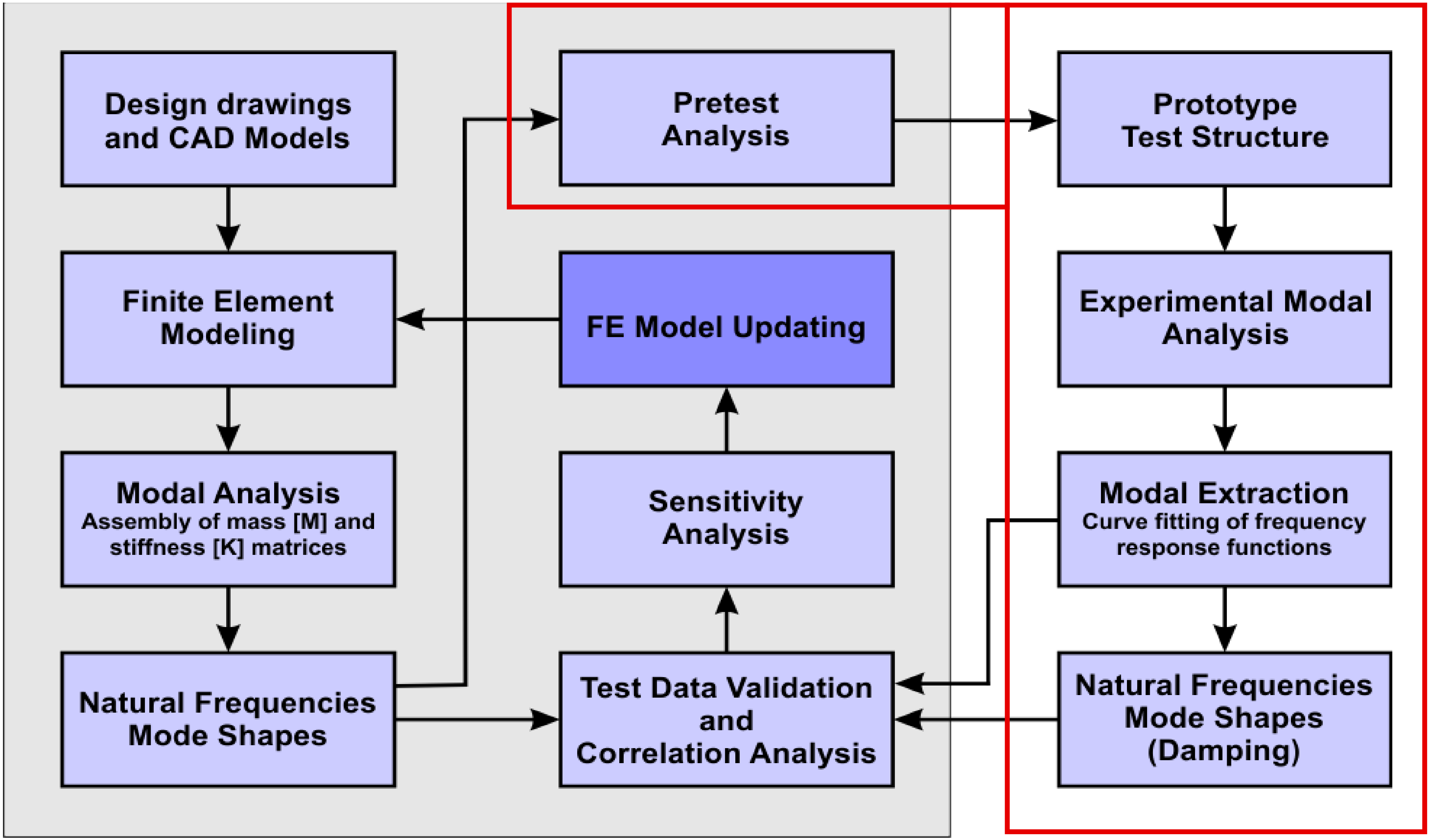
Simulation

- Physical uncertainty
  - Boundary conditions & joints
  - Material properties
  - Geometry
- Modelling
  - Conceptual & mathematical model
  - Discretization, element type
- Analysis
  - Non-linearity
  - Master DOF selection
- Manufacturing tolerances
  - Thickness tolerances
  - Fiber alignments
- In service variations
  - Temperature
  - Humidity

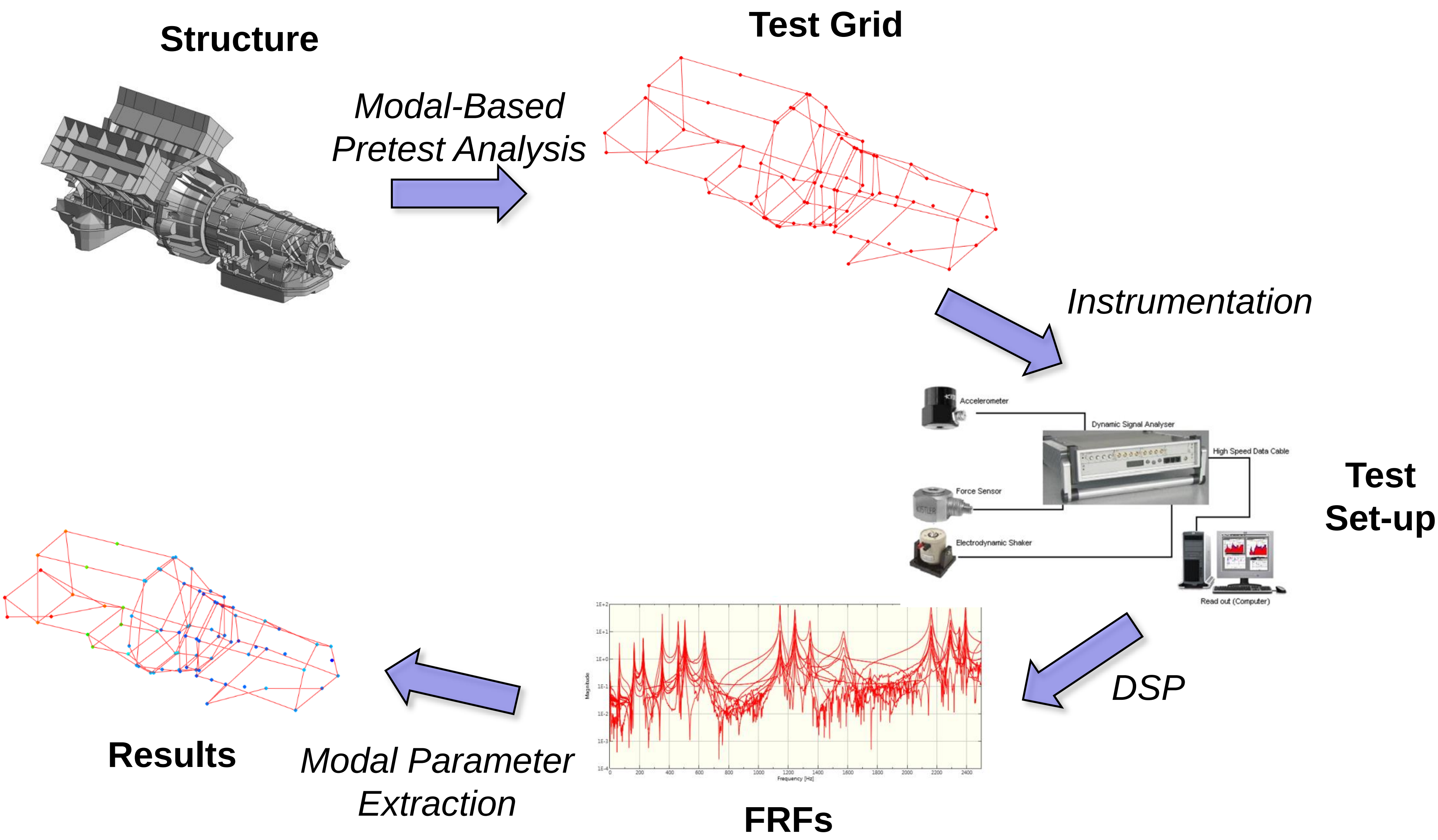
Testing

- Test definition
  - Fixture
  - Mounting procedure
  - Excitation method
  - Transducer location
- Dynamic loading
- Instrumentation
  - Calibration
  - Distortions
- Data acquisition
  - Digital signal processing
  - Measurement formulation
- Modal parameter estimation
  - Mathematical models
  - Selected poles

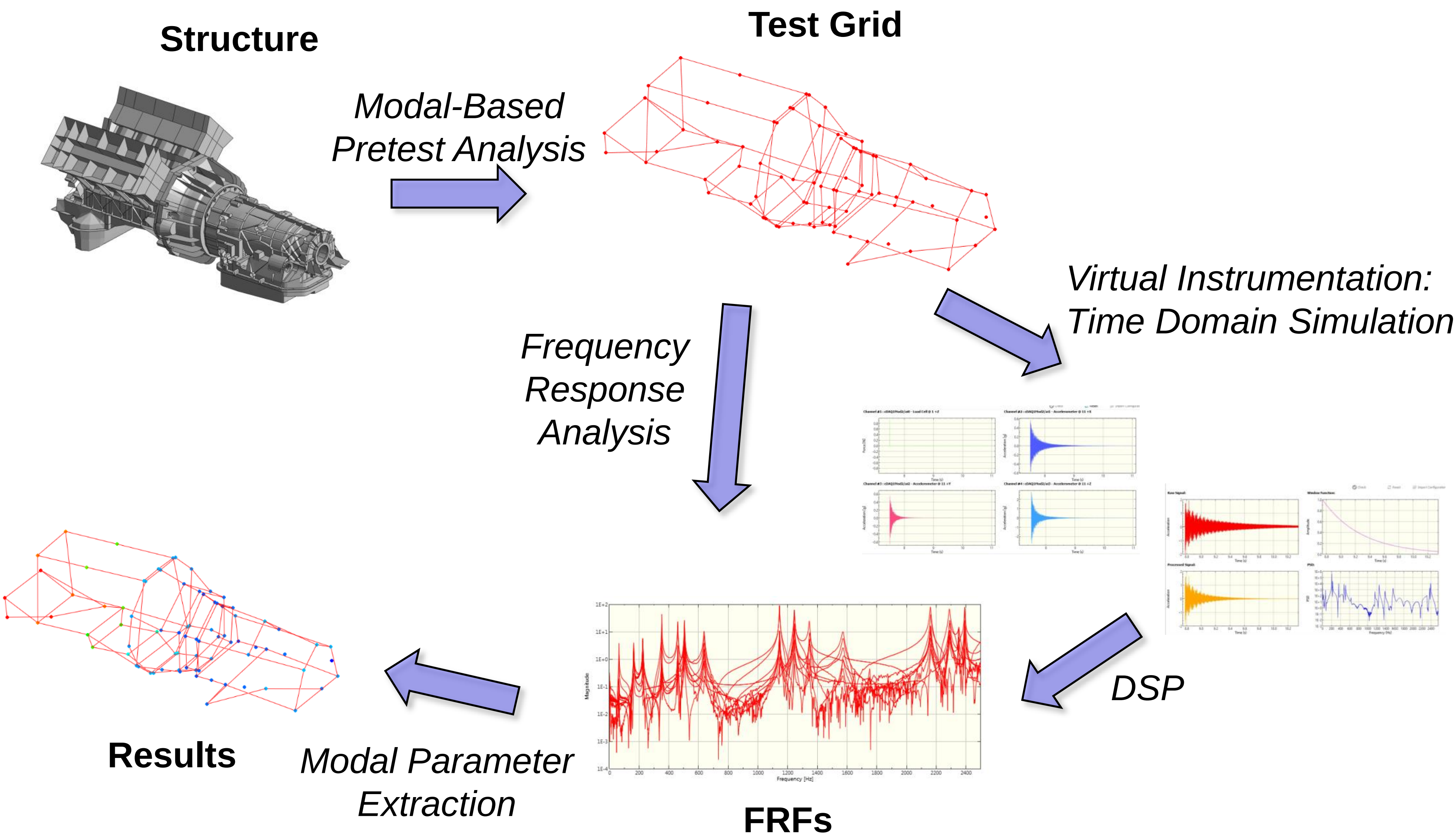
Modal–Based Validation and Model Updating



The Physical Modal Pretest and Testing Workflow

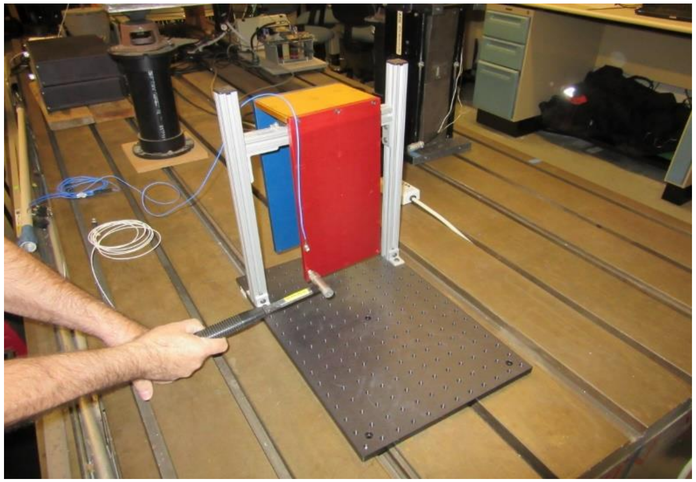


The Virtual Modal Testing Workflow



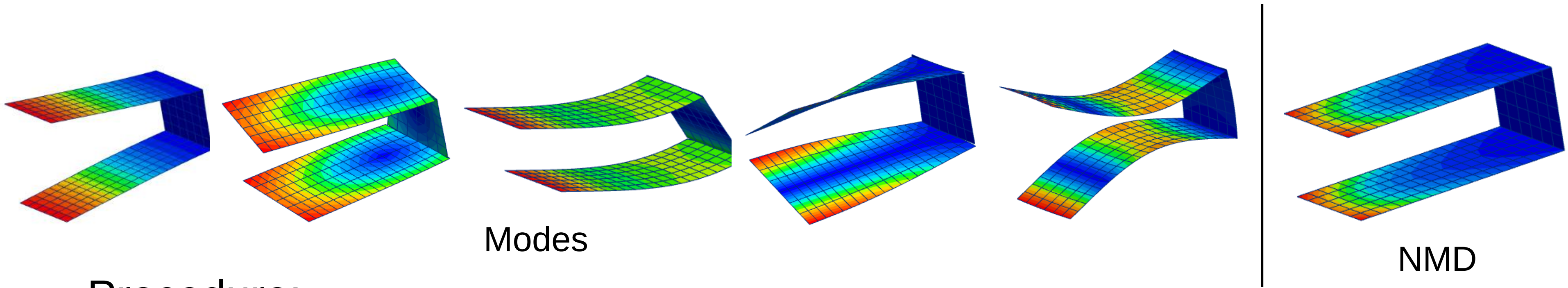
Modal-Based Pretest Analysis

- Use a baseline FE model to plan and optimize modal tests
- Baseline finite element analysis to predict mode shapes in frequency band of interest. FEMtools can use its internal modal solver or pilot external solvers like Nastran (MSC, NX, Optistruct), Ansys, Abaqus, LS-Dyna,…
- Results are post-processed for:
  - Target mode selection
  - Selection of candidate sensor locations and directions
  - Selection of actuator and suspension location and direction



Sensor Selection Example

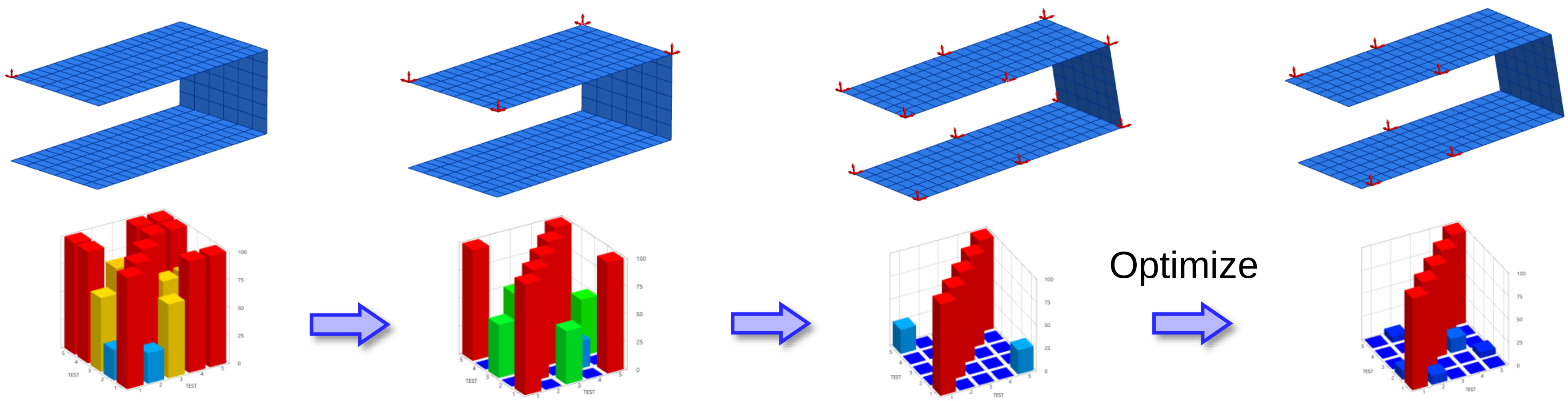
- Structure



Modes

NMD

- Procedure:
  - Make an initial DOF selection and check the auto-correlation
  - Refine the initial DOF selection while monitoring the auto-correlation

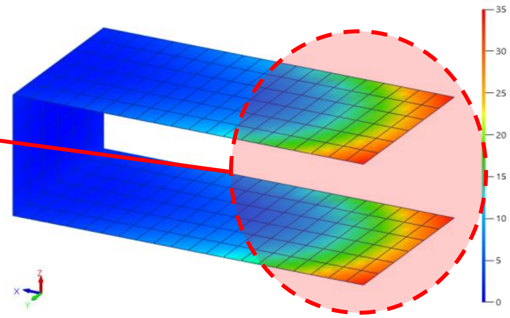


3 DOFs 12 DOFs 36 DOFs 18 DOFs

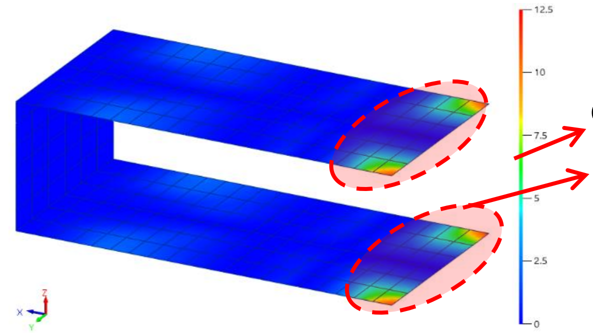
Interpreting the Sensor Selection Metric

In general, all modes show a movement in these areas

Average NMD



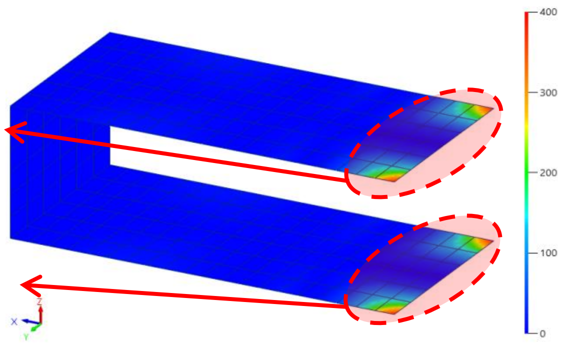
Minimum NMD



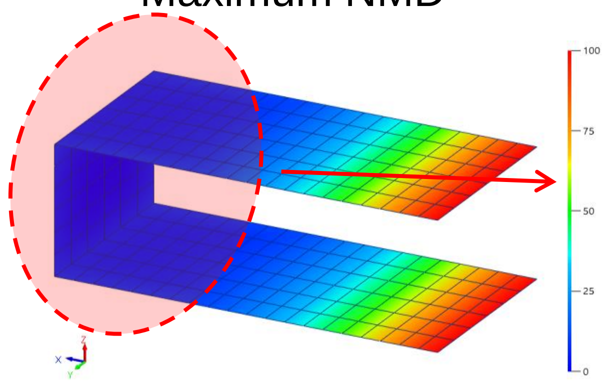
In these areas the structure moves, and this for each one of the considered modes.

This is the product of the Average NMD and Minimum NMD. In these areas there is a good overall movement, and at least a small movement for each mode. These are good **sensor** locations.

Weighted NMD



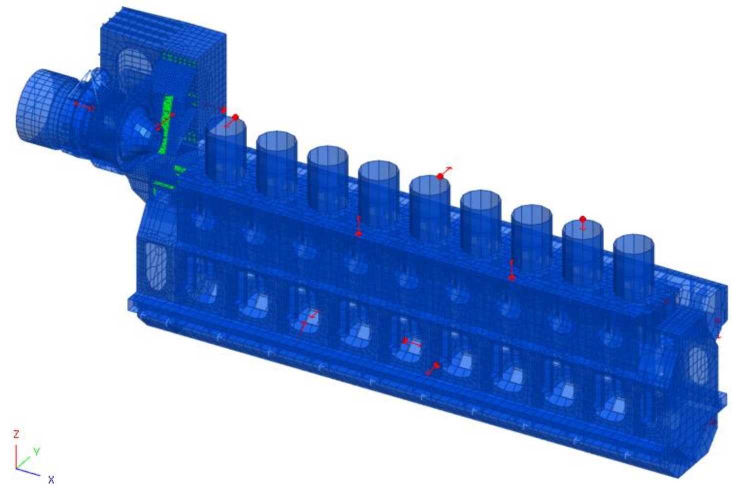
Maximum NMD

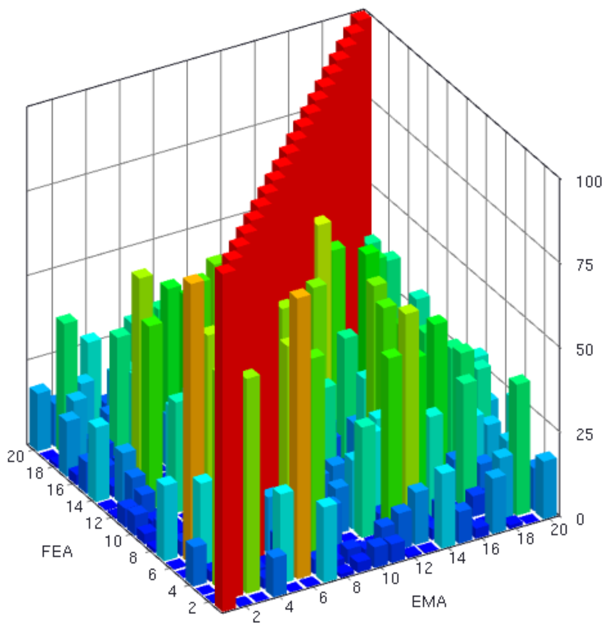


There is no movement, and this for all the modes. These are good **suspension** points.

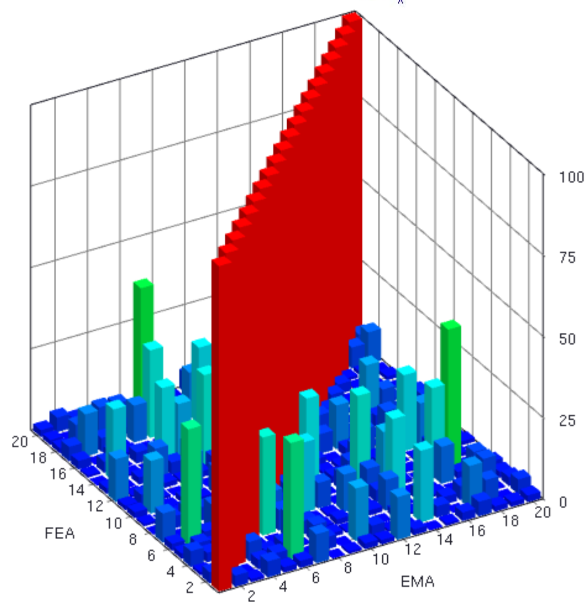
Comparing Different Methods for Sensor Selection

- Target:
  - 20 mode shapes
  - 20 sensors normal-to-surface





Selection using NMD

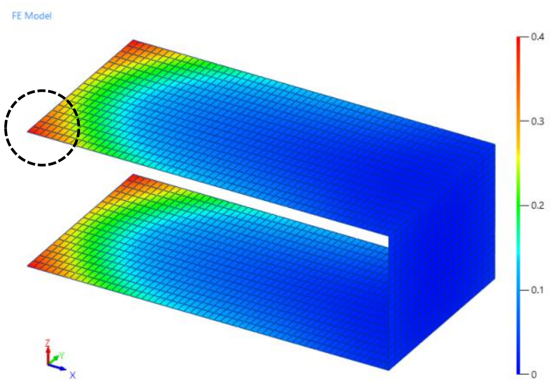


Sensor selection using MAC

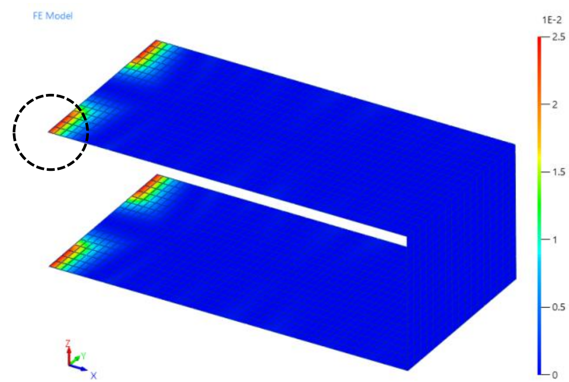
Excitation Location

- Find candidate location where all modes of interest can be excited
  - Locations that have a high average modal displacement or nodal kinetic energy
  - Locations and directions with that result in high average modal participation
- Evaluate the candidates based on practical considerations, detailed modal participation analysis (MPA),
modal indicator functions (MIF),…

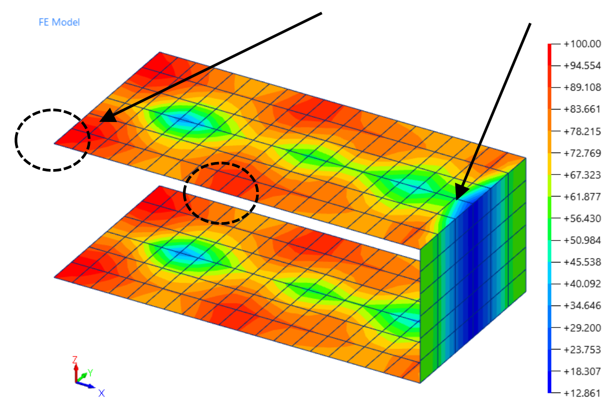
Mode	Freq [Hz]	MPA	MPA
1	53.61	8.507 %	0.000 %
2	129.14	2.361 %	0.000 %
3	188.57	3.435 %	6.031 %
4	310.52	14.571 %	0.000 %
5	420.33	8.972 %	0.000 %
6	449.14	11.770 %	0.000 %
7	553.78	7.941 %	93.967 %
8	1000.95	18.511 %	0.000 %
9	1064.93	17.402 %	0.000 %
10	1225.77	6.530 %	0.002 %



Average NMD

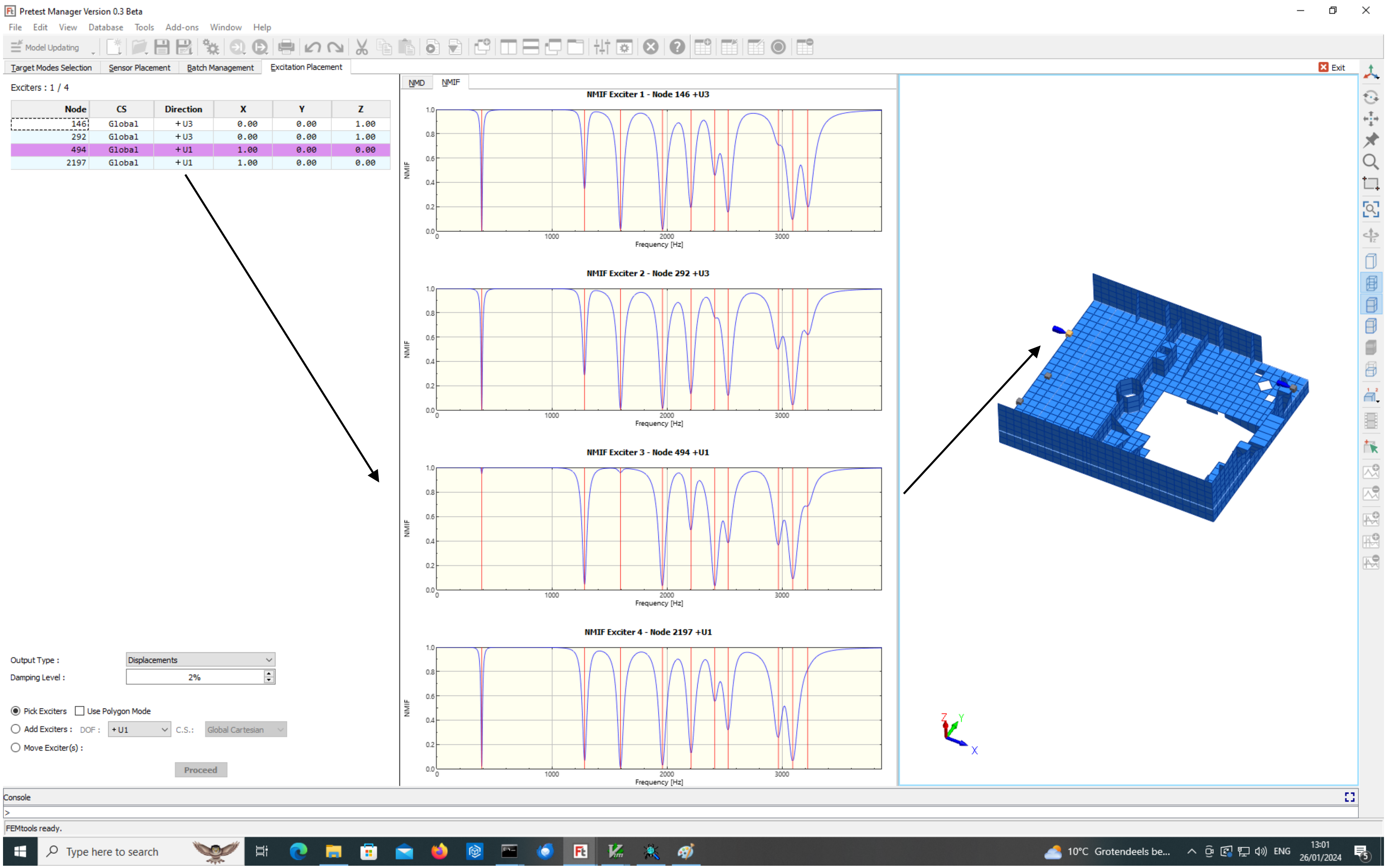


Weighted NMD



Mode Participation Map

Pretest NMIF using Simulated FRFs



Some Applications

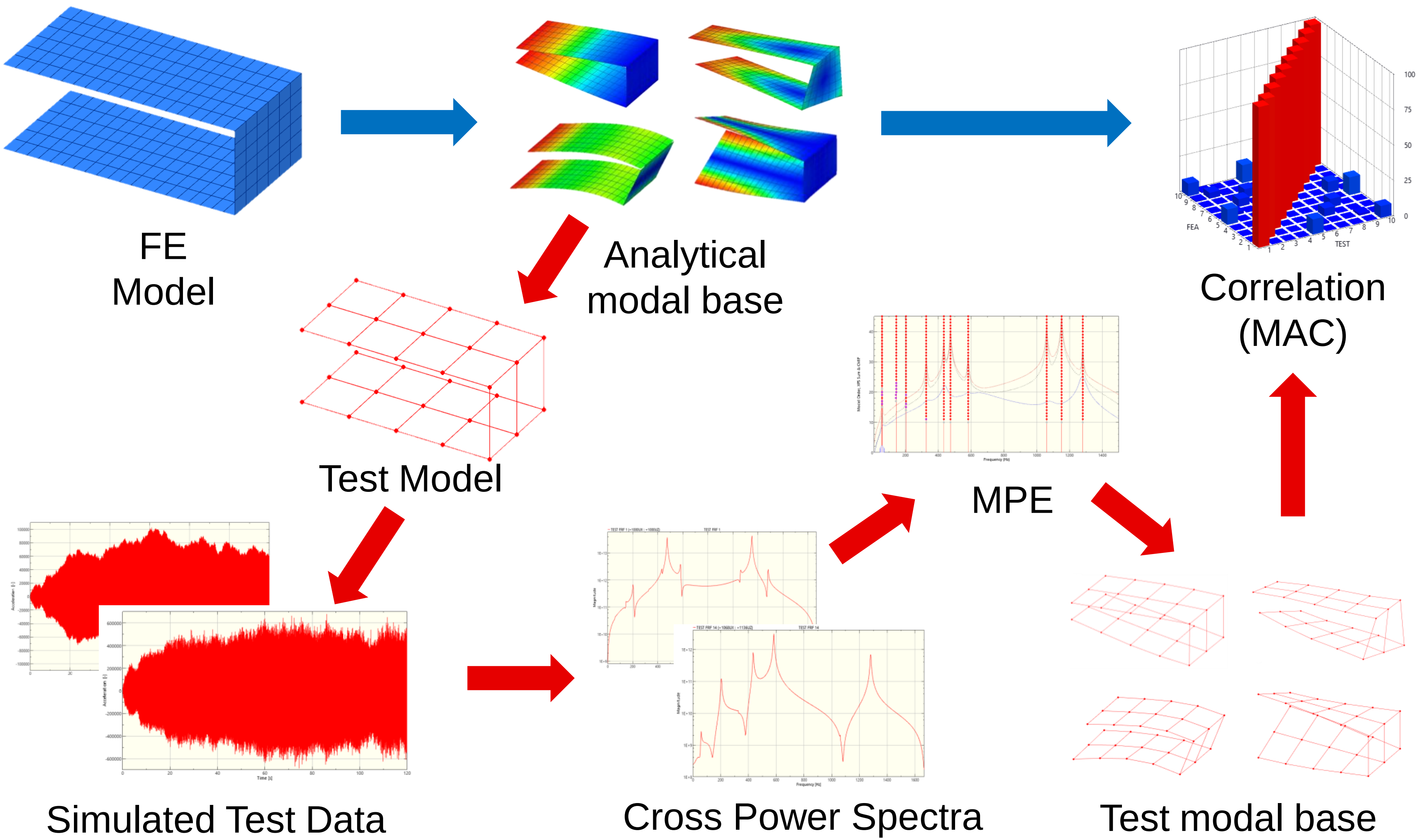
- Automation for parametric studies
- Decide on parameters for excitation signal, time domain simulation, DSP, modal parameter extraction
- Selection of reference channels for OMA with roving sensors
- Additional pretest analysis tasks
  - Simulation for Rigid Body Properties Extraction (RBPE)
  - Mass loading evaluation
  - Sensor batch creation
  - Stress analysis to avoid overloading
- Test model preparation:
  - Computing normal directions at test locations
  - Export the test model to test software

Automation for Parametric Studies

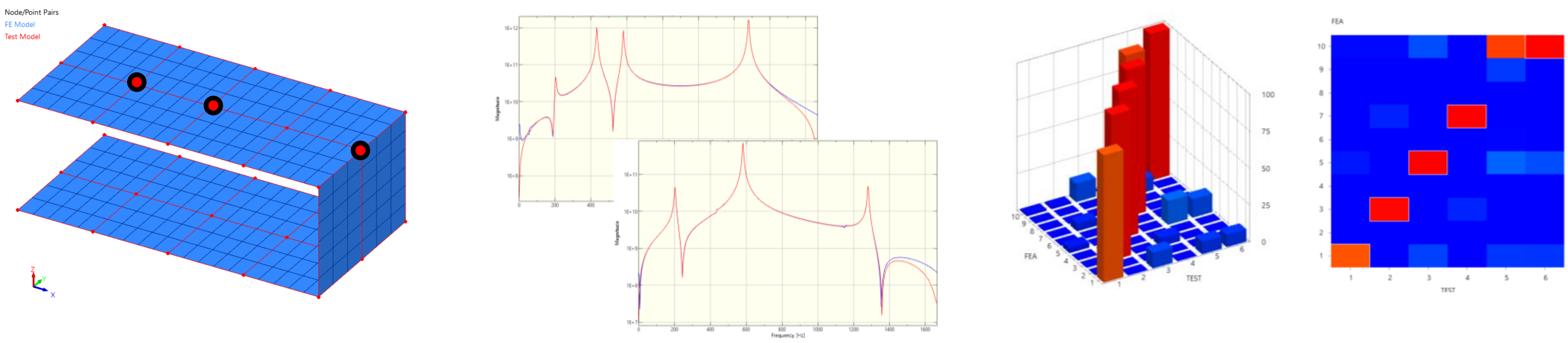
- Automation through scripting can used for parametric studies and to study uncertainties and variability.
- Excitation
  - Location, direction, amplitude
  - Excitation signal (impact, chirp, random, burst random)
- Time domain simulation
  - Signal length, time step
- DSP
  - Blocksize, windows, filtering
- MPE
  - Maximum order
  - Min and max frequency
  - Pole selection

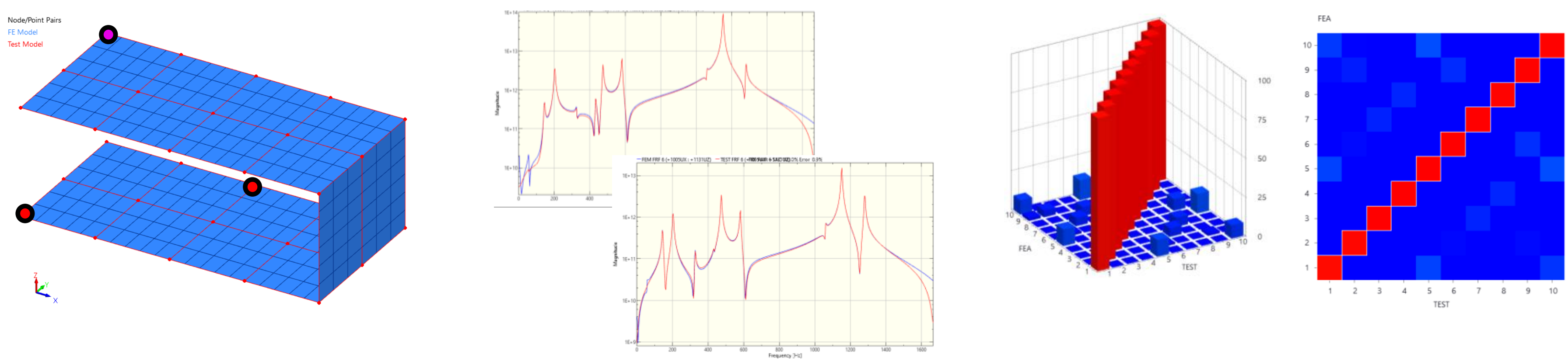
```
clear all

search fem format femtools file jimbeam.fdb

compute mass stiffness
dynamic vector 10 fmin 10

define tdssignal  1 node 1000 dof +uz type force

define tdssignal  2 node 1000 dof +ux type acceleration
 ...

set tds length 120 step 0.0003
tds generate signal 1 type random amplitude 0.5 distribution uniform
tds plot signal 1
tds compute
tds convert force off # copy signals to test database

  ...

dsp xps blocksize 1024 reference 61 73 56

set mpe maxorder 45
set mpe minfreq   10
set mpe maxfreq 1500
set mpe type complex

# Extract the modes
mpe poles extract
mpe poles store
mpe modes extract

pair mode all

examine mac
matrix mac
```

Example: OMA Simulation



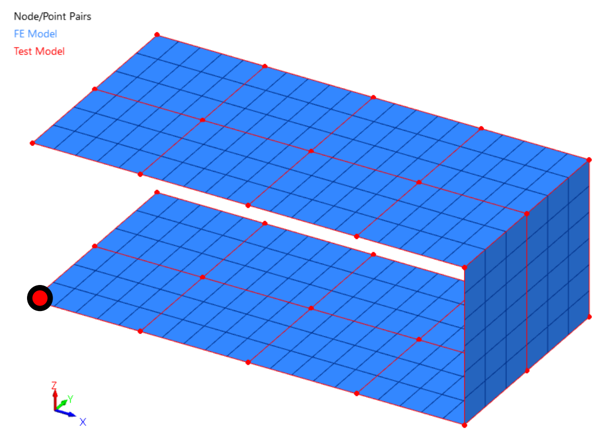
Reference Channel Selection for OMA

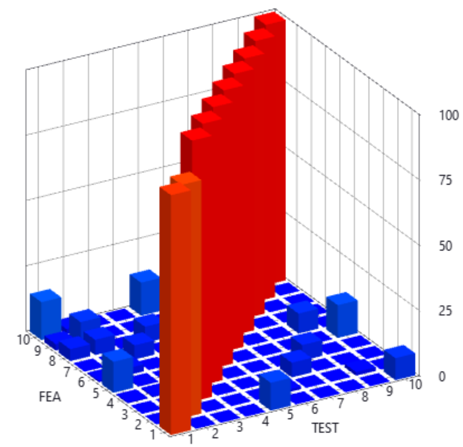


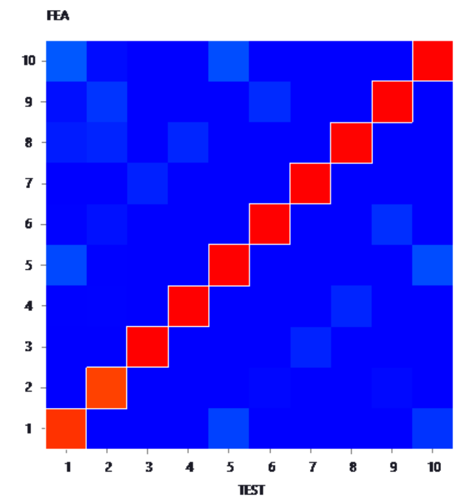


Reference Channel Selection for OMA

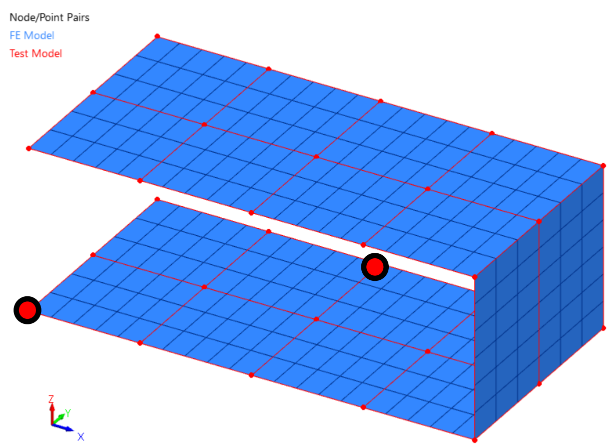
1 Reference Channel:

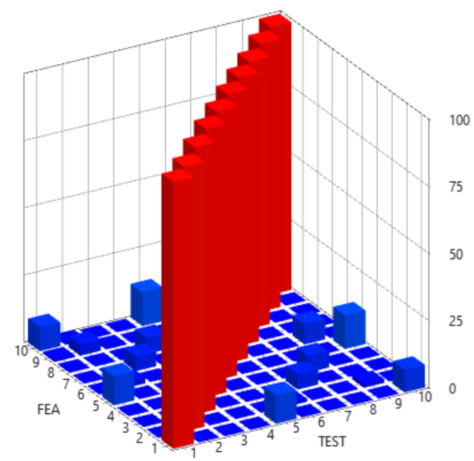


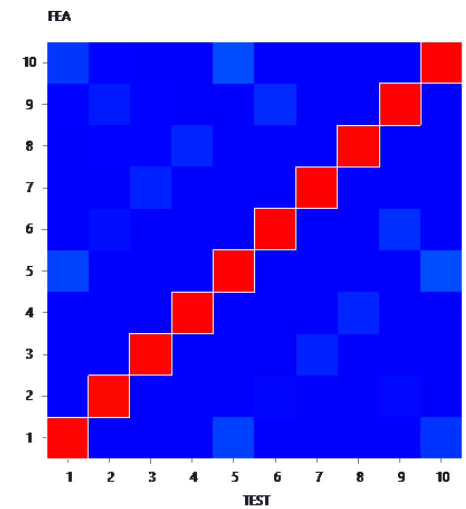




2 Reference Channels:

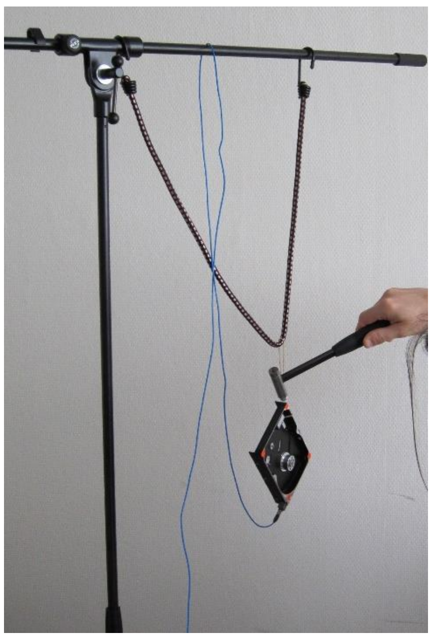


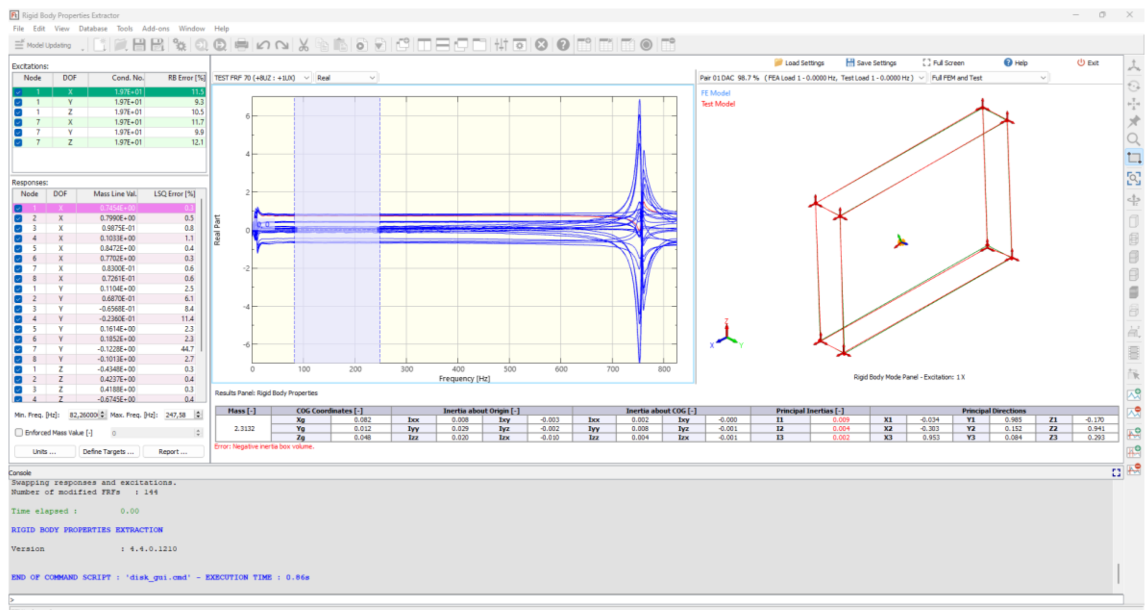




Simulation for Rigid Body Properties Extraction (RBPE)

- Indirect experimental method using Frequency Response Functions (FRF)
- Extract mass properties from the mass line of FRFs
- At least 3 excitation DOFs are required + additional requirements
- At least 6 response DOFs
- Learn how to use RBPE with simulated FRFs computed from an FE model with known rigid body inertia properties

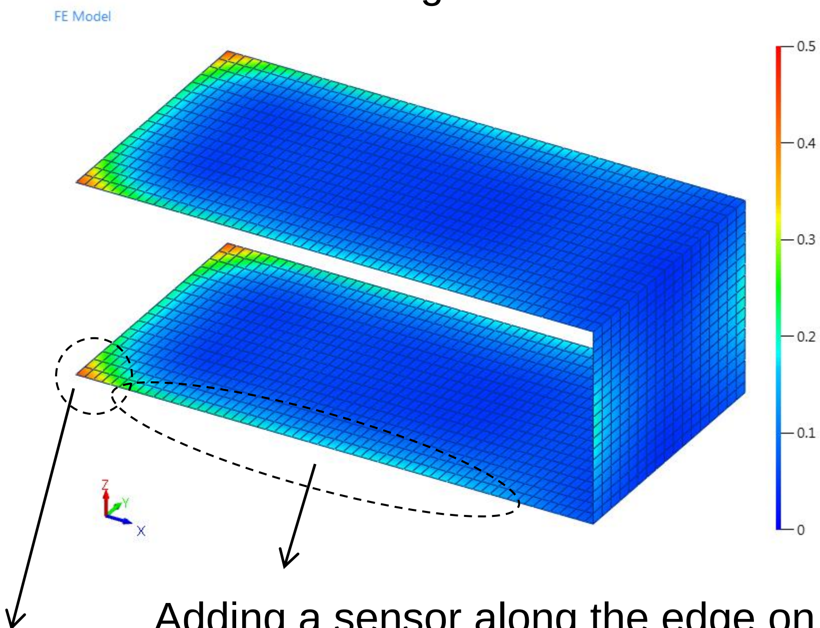




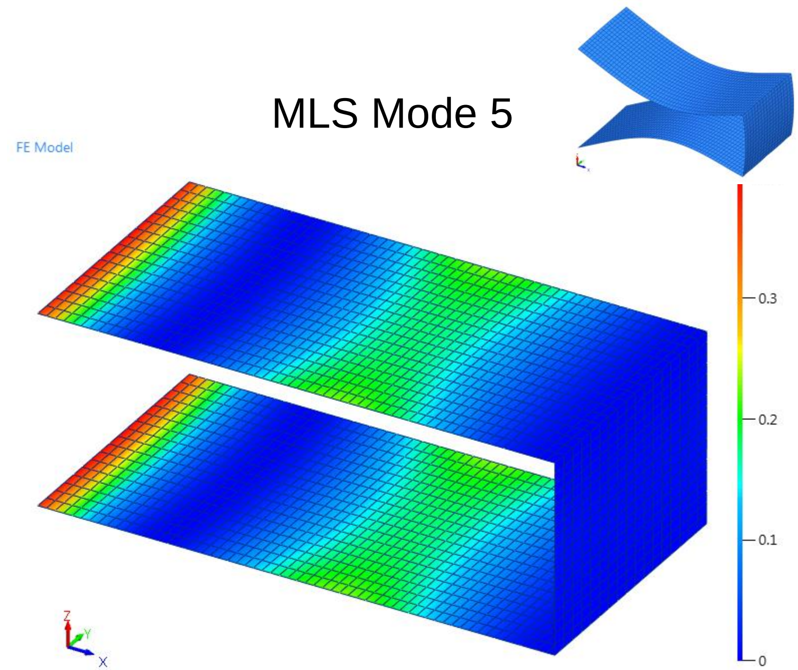
Mass Loading Sensitivity

- Evaluate the impact of the sensor mass on the resonant frequencies
- Enter : **Sensor Mass** = 0.005 (= 5g), **Sensitivity Type** = Relative

Average MLS



MLS Mode 5



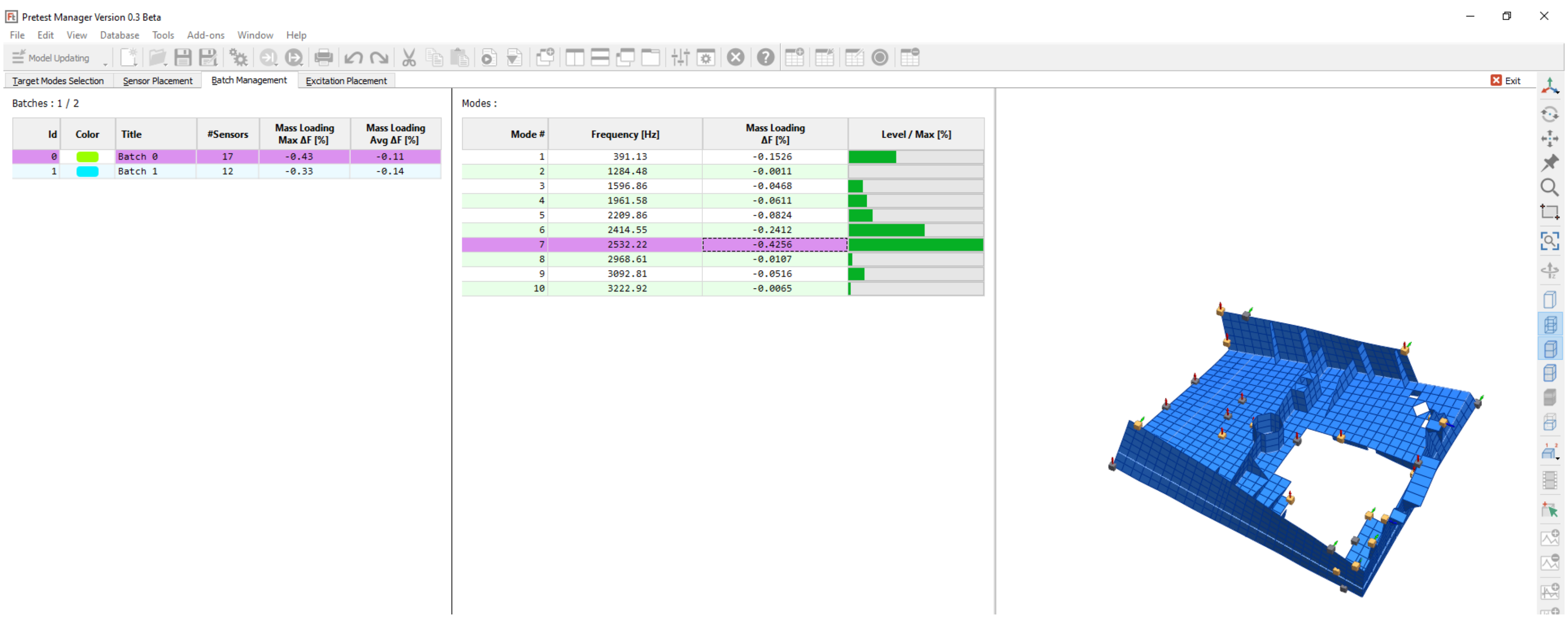
Adding a sensor along the edge on average lowers the frequency with 0.2%

Adding a sensor at the corner on average changes the frequency with 0.5%

- Conclusion: It is not advisable to use more than 1 sensor.

Create Batches of Sensors with Balanced Mass Loading

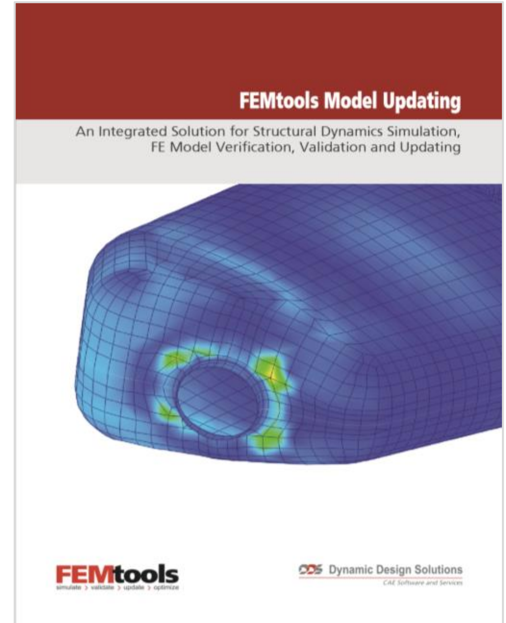
- Group sensors in batches for roving measurements (fixed shaker)
- Each batch should have a similar mass loading impact on the resonant frequencies



Conclusions

- Integration of simulation (FEA), signal processing and modal parameter extraction enables the Virtual Modal Testing process
- Combined with modal and FRF-based pretest analysis, the test setup can be optimized for specific goals like FE-test correlation analysis, rigid body properties extraction,…
- Automation through scripting of the workflow can used for parametric studies and to study uncertainties and variability.
- Additional physics can be added for more realism, like for example hammer tips, shaker model, sensor sensitivity, mounting properties, …
- Quality of the virtual process depends on the validity of the FE model !

For More Information…



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