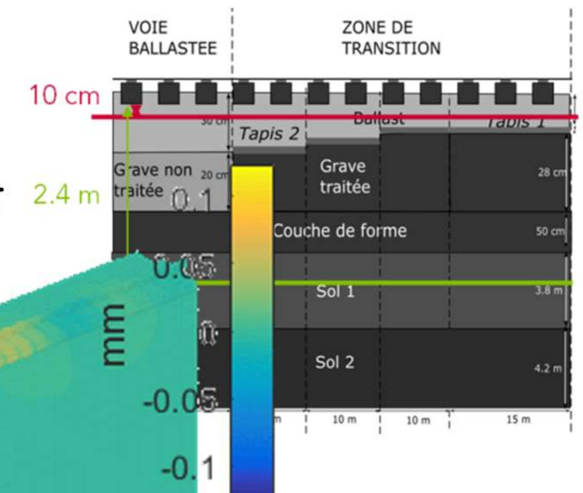
Vibrations /Modal analysis

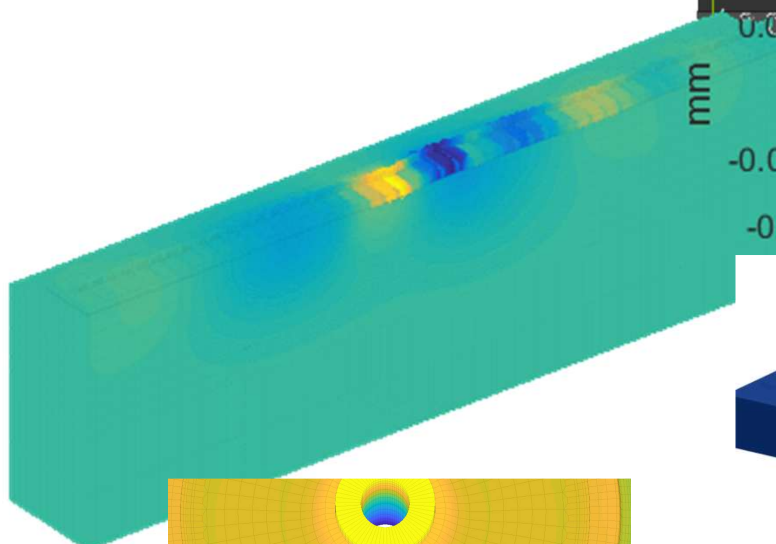
Etienne Balmes — Ensam/PIMM, SDTools
Mathieu Corus — CentraleSupelec, EDF

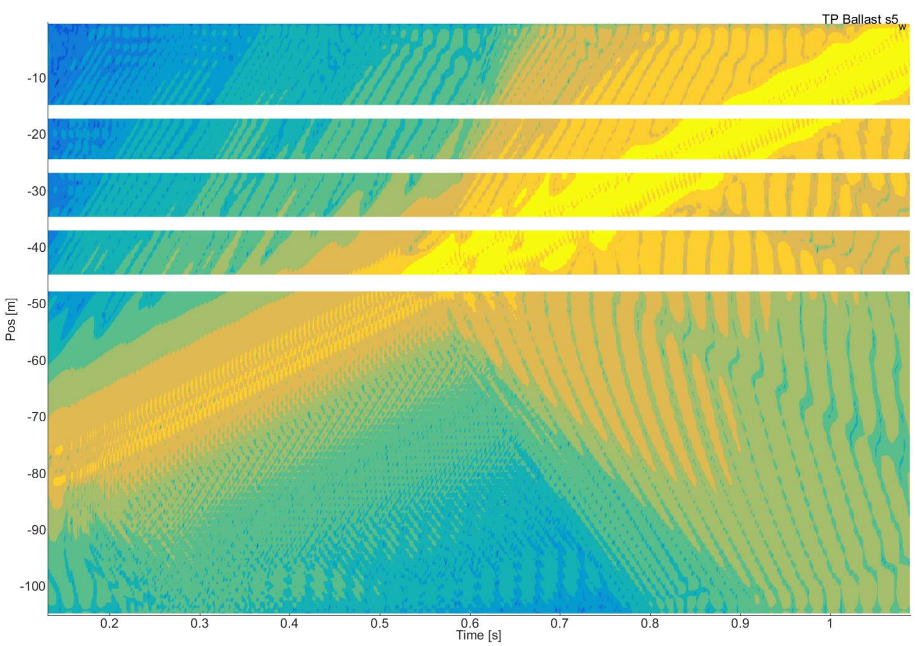
http://savoir.ensam.eu/moodle/course/view.php?id=1874

Track/train interaction

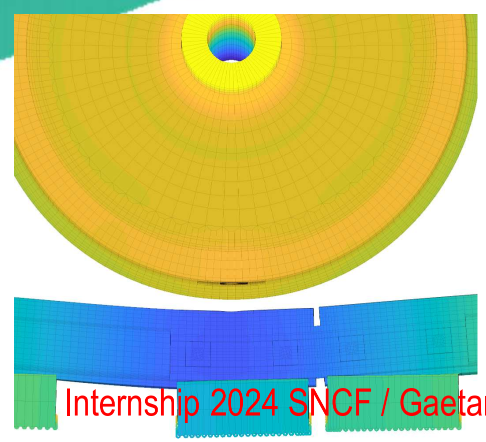
- Piece-wise periodic structure with 15e3 node per 60cm slice
  - Full 3D > 5h, 90 Gb
  - Reduced 23 min, 100 Mb
- Scientific issues
  - model reduction, wave propagation, random properties of ballast
  - Rail/wheel contact, fatique



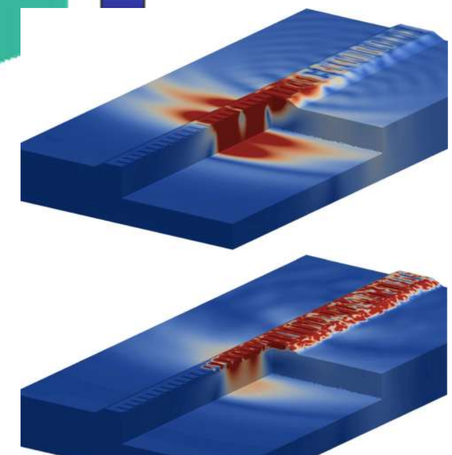




Ph.D. Elodie Arlaud (2014-16), Hadrien Pinault (2017-2020)



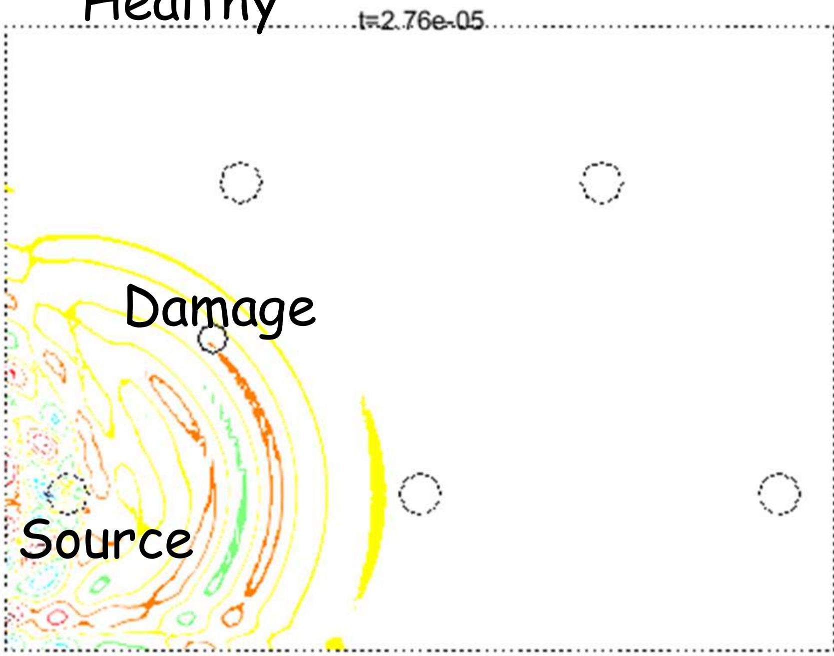
Internship 2024 SNCF / Gaetan Guillet / Olivier Vo Van



Lucio de Abreu Corrêa & al.

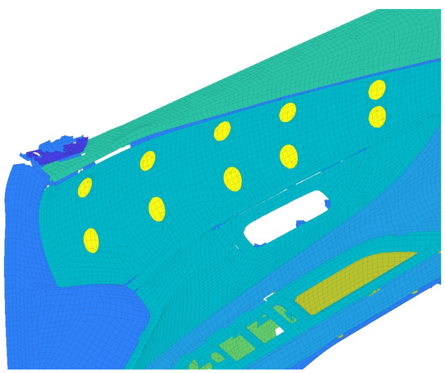
SHM transients

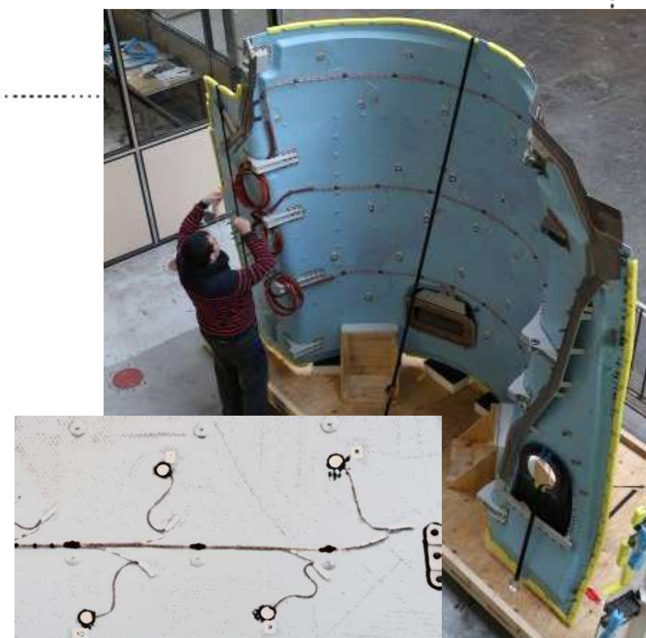
Healthy



Damaged-healthy

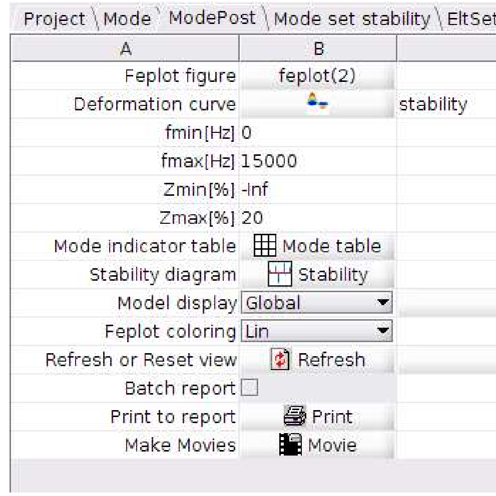
- Electrical signals used for measurement
- Damage acts as a source in healthy-damaged signal





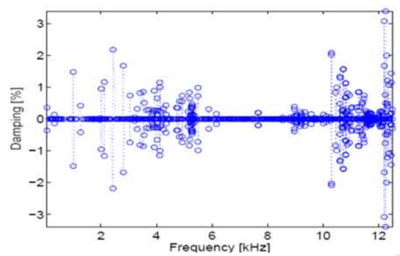
Brake squeal simulation

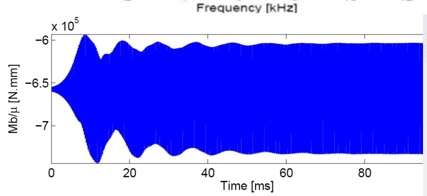
- 1 full time @ SDTools
  (Audi, Daimler, Stellantis, CBI, …)
- Advanced solvers in frequency & time
- Objectives
  - Industrial design tools
  - Parametric model reduction
  - Optimized transients

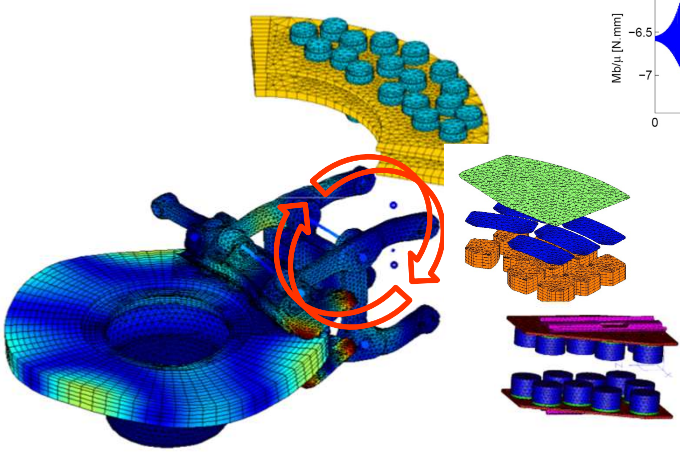


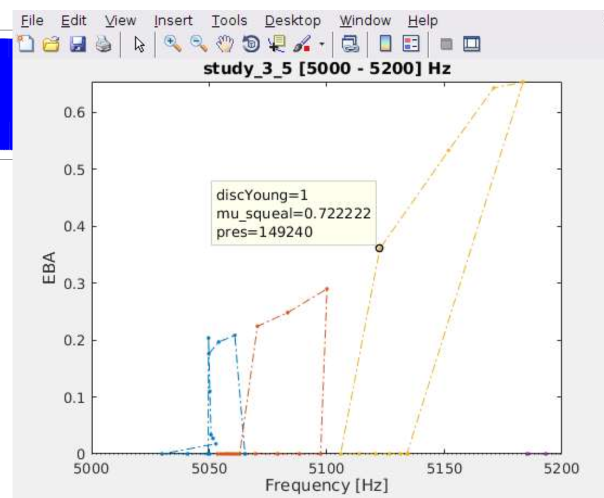
A	B	C
Feplot figure	feplot(2)	
Deformation curve		stability
fmin[Hz]	0	
fmax[Hz]	15000	
Zmin[%]	-Inf	
Zmax[%]	20	
Mode indicator table	Mode table	
Stability diagram	Stability	
Model display	Global	
Feplot coloring	Lin	
Refresh or Reset view	Refresh	
Batch report		
Print to report	Print	
Make Movies	Movie	

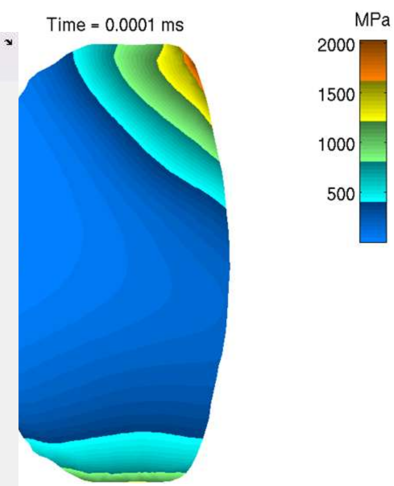
Freq	Damp	SqC	EBA	VNSD
1290	0.01%	-0.02	0E0	8.1
1455	0.01%	-0.01	0E0	8.1
1519	0.24%	-0.48	0E0	5.9
1991	0.07%	-0.15	0E0	7.2
2220	0.03%	-0.07	0E0	7.6
3325	0.03%	-0.06	0E0	7.4
3441	0.05%	-0.11	0E0	6.7
5050	-0.02%	0.05	1.751E-1	5.6
5058	0.76%	-1.52	0E0	2.
5134	0.85%	-1.70	0E0	5.5
5281	0.19%	-0.39	0E0	5.2
6260	0.03%	-0.06	0E0	2.8
6362	0.02%	-0.03	0E0	8.2
7029	0.00%	-0.00	0E0	5.38
7216	0.03%	-0.06	0E0	5.8
7368	0.03%	-0.06	0E0	6.0
8604	-0.03%	0.06	6.559E-1	1.3
8608	0.03%	-0.06	0E0	1.3
8777	0.21%	-0.42	0E0	1.0
9080	0.30%	-0.61	0E0	1.1
9308	0.45%	-0.90	0E0	1.5
9344	-0.00%	0.01	3.259E-2	2.1
9408	0.73%	-1.46	0E0	8.8
9513	0.15%	-0.31	0E0	4.1
9603	0.11%	-0.22	0E0	3.8









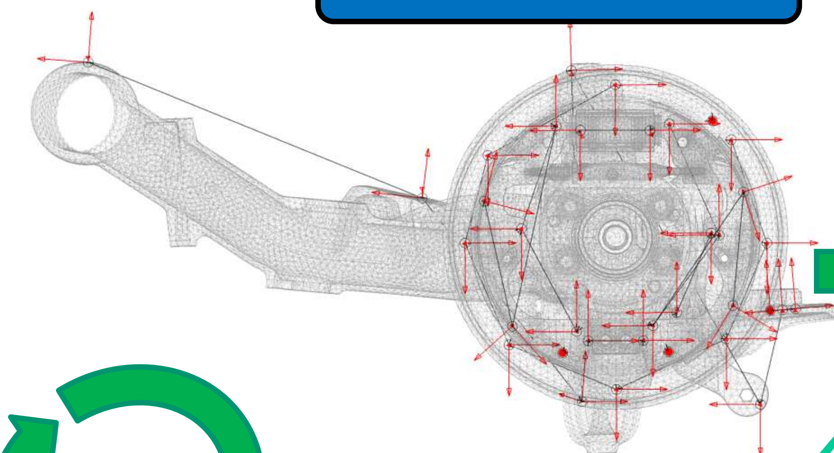


Squeal testing : combined test/FEM

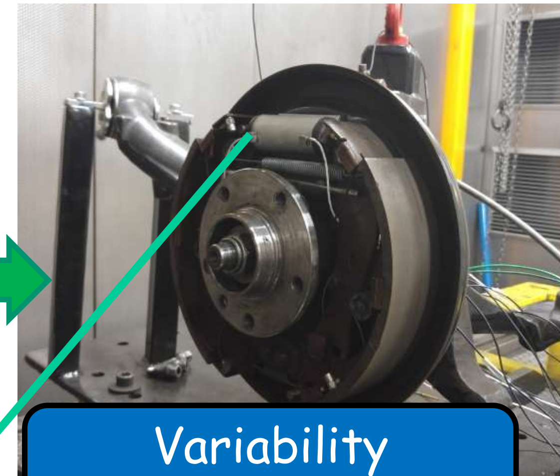
Full FEM

Update :
1. Geometry
2. Parameters
3. component contacts

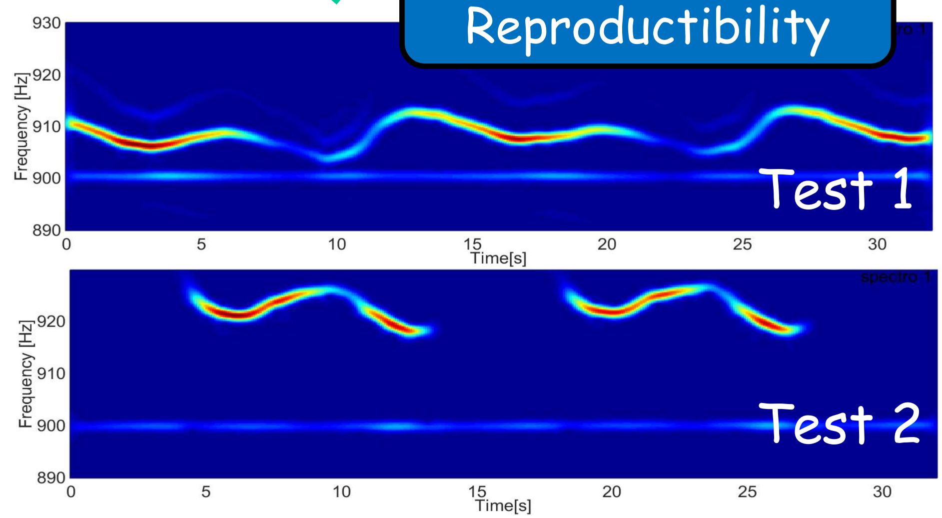
Sensor placement



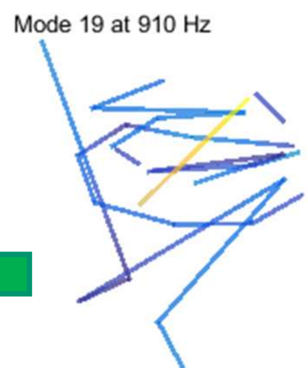
Real test



Variability
Reproductibility

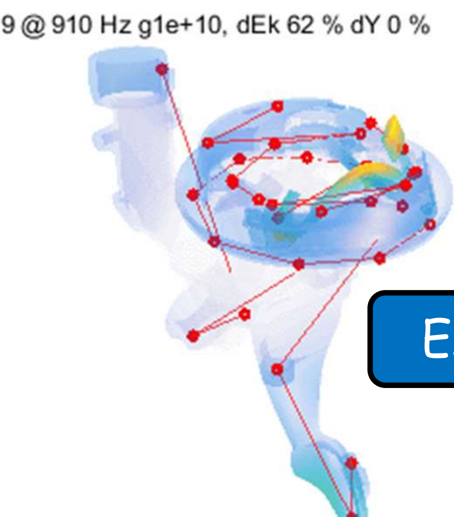


Squeal : time varying with wheel position



Shape extraction

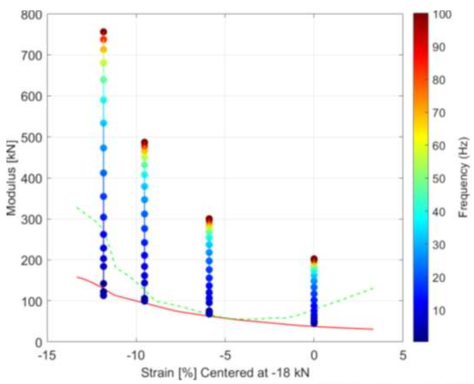
Expansion

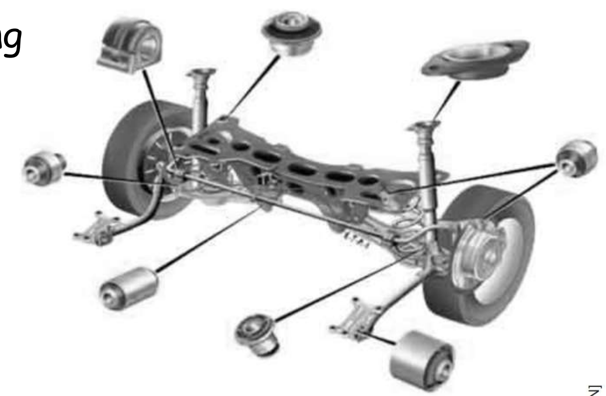


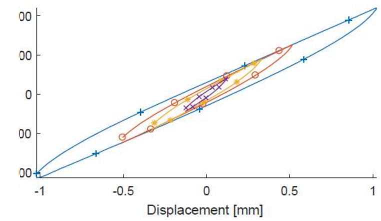
Viscoelastic damping

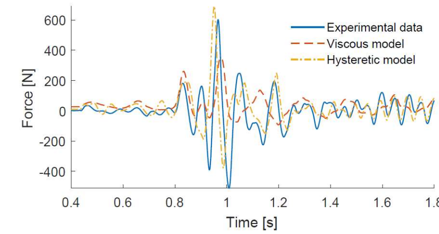
Scientific problems with damping

- 0D (structure) vs. 3D (material + geometry) modeling
- Damping in complex structures
- Homogeneization in composites

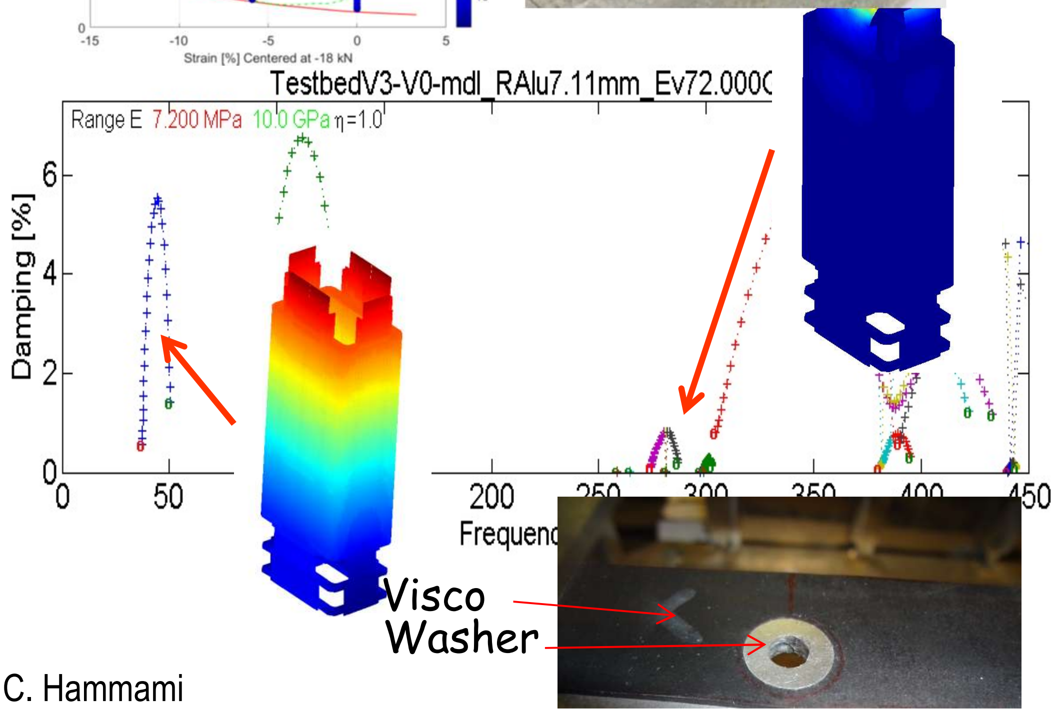




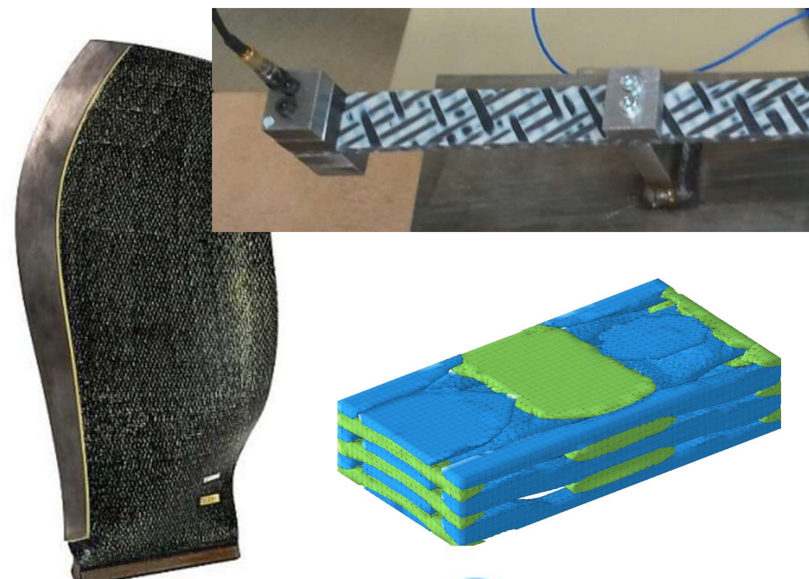




Ph.D. R. Penas 21



Ph.D. C. Hammami



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SDT core focus

SDT (software since 1995, 700+ licenses)
SDTools (company since 2001
4 engineers (develop + interact with clients & PhDs)

- FEM simulations
- System models (model reduction, state-space, active control)
- Experimental modal analysis
- Test/analysis correlation, model updating

Simulation

Validation

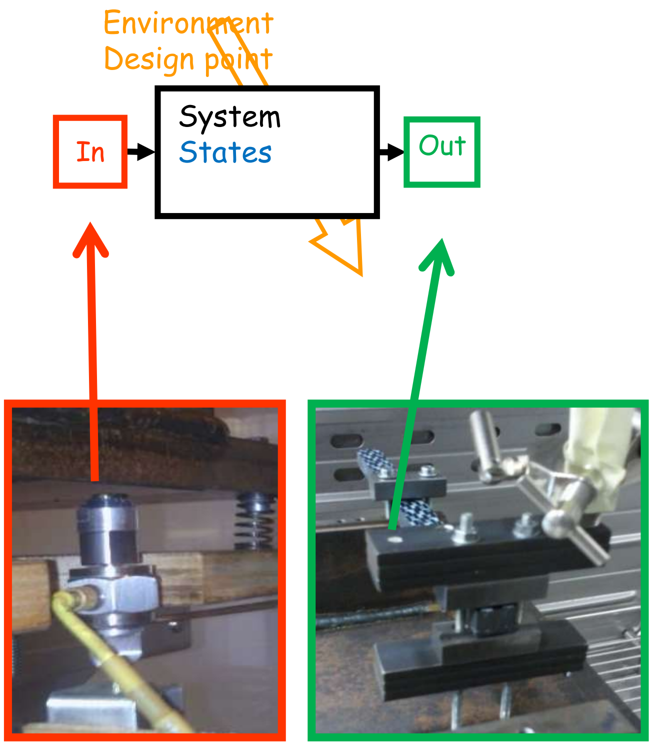
CAD/Meshing
FEM
Simulation
Testing

CATIA, Workbench, …
NASTRAN, ABAQUS, ANSYS,...
Adams, Simpack, Simulink,...
LMS TestLab, ME-Scope, …

- Necessity: programmatic access to all steps
- Proposed solution: flexible toolbox & custom applications
- Base commercial library : for quality, durability, capitalization
- Consulting/research

Arts et Métiers Institute of Technology

What is a system ?



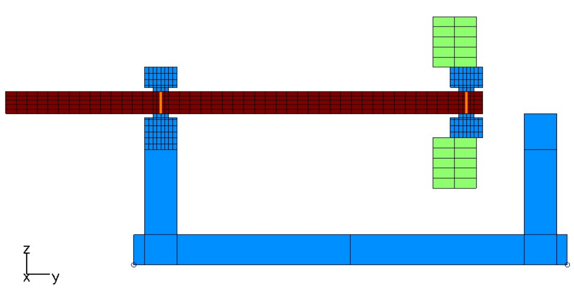
- **Inputs $u(t)$** : hammer with force measurement
- **Outputs $y(t)$**
  - Test : vibrometer on testbed
  - Computation : stresses
- **State $x(t)$**
  - Displacement & velocity field as function of time

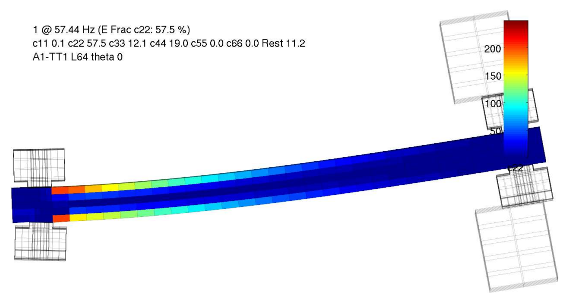
$$\{\dot{x}(t)\} = f(x(t), u(t), p, t) \qquad \text{evolution}$$

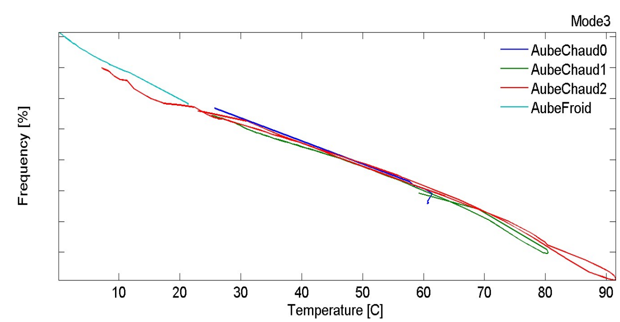
$$\{y(t)\} = g(x(t), u(t), p, t) \qquad \text{observation}$$

- **Environment variables p**
  - Dimensions, test piece (design point)
  - Temperature (value of constitutive law or state of thermo-viscoelastic)

- Feature : function of output (example modal frequency)

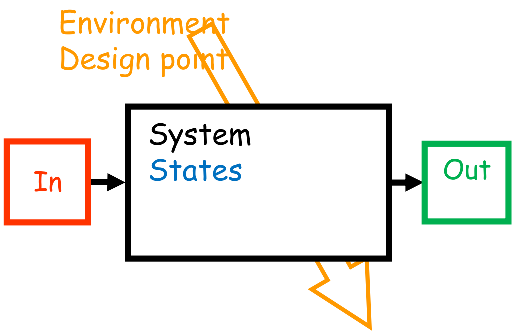






Simple example : modified Oberst test for 3D weaved composite test

System models : nature & objectives?

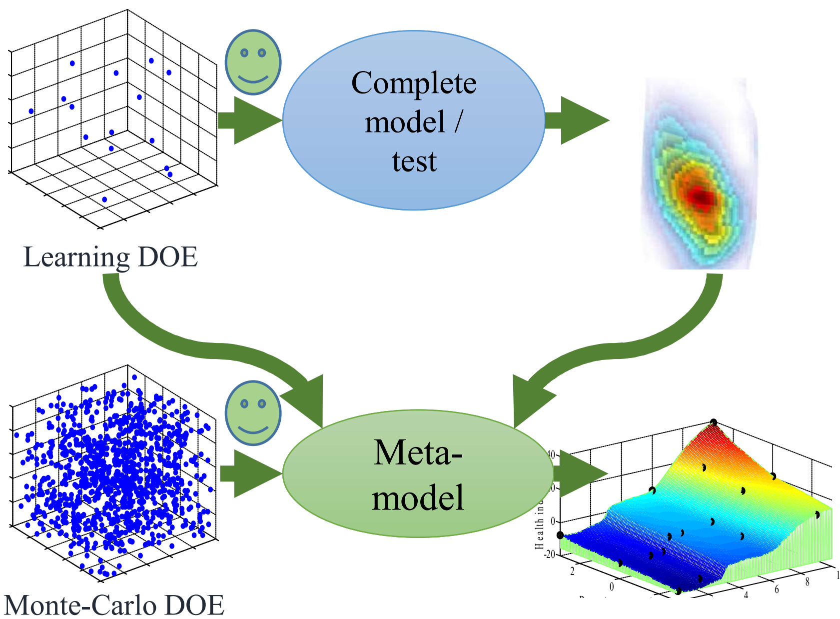


What is a model

- A function relating input and outputs
- For one or many parametric configurations

Model categories

- Behavior models (meta-models)
  - Test, constitutive laws, Neural networks
  - Difficulties : choice of parametrization, domain of validity
- Knowledge models
  - Physical principles, low level meta-models



Why do we need system models ?

Design

- Become predictive : understand, know limitations
- Perform sizing, optimize, deal with robustness

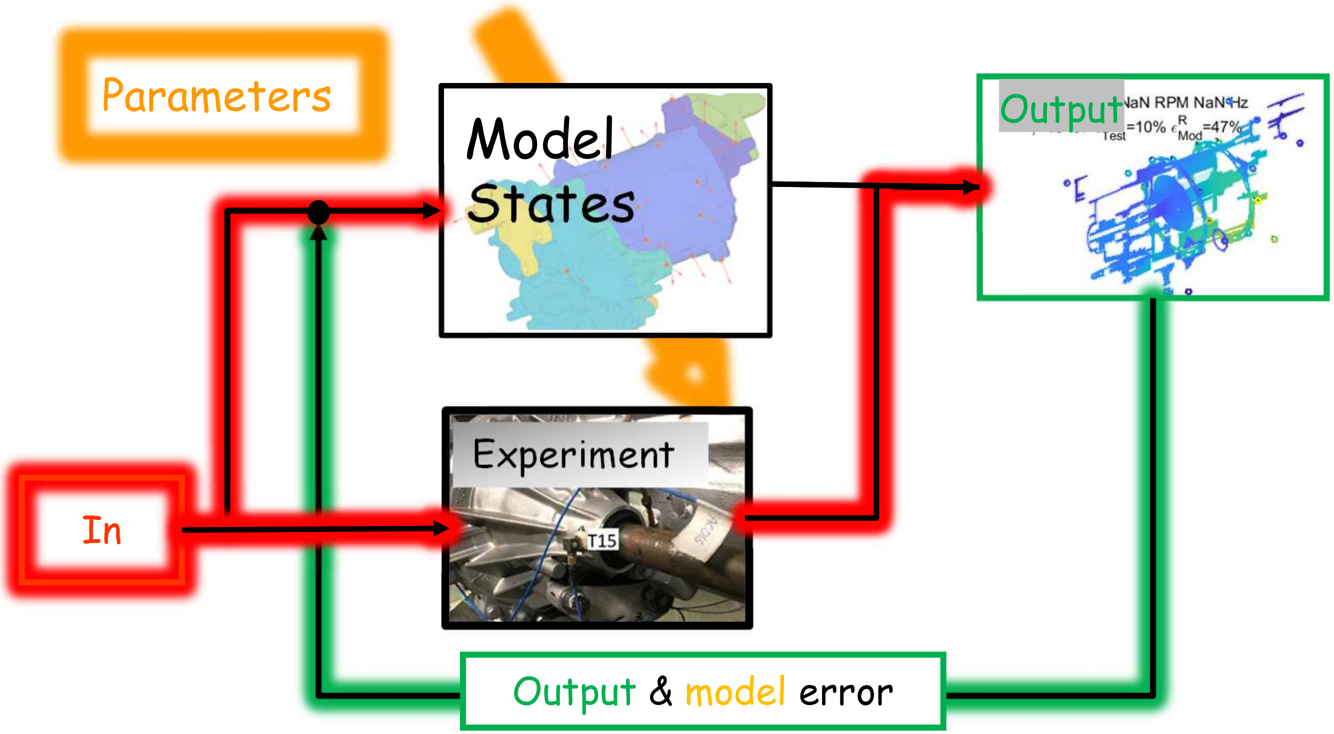
Certify

- Optimize tests : number, conditions
- Understand relation between real conditions and certification
- Account for variability

Maintain during life

- Design full life cycle (plan maintenance)
- Use data for conditional maintenance (SHM)

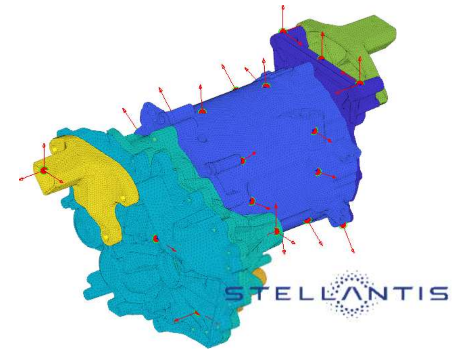
Graphical course outline



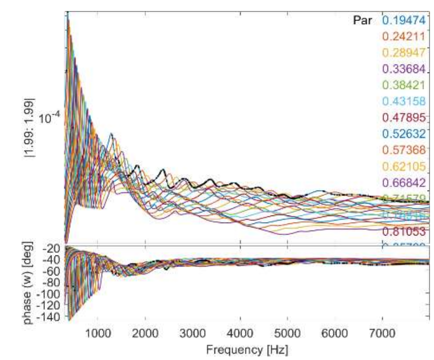
1. Test characterization : input / system, output (space & time & frequency)
   C3: signal, C5: Experimental modal analysis
2. Parametric system models for online use
   C1-C2: modes and system models, C4: model reduction, C6: sensitivity, C7: reanalysis, C9: damping, C10: component mode synthesis, C11: subspace methods
3. Hybrid test/FEM models
   C8 : test/analysis correlation, expansion, C12 updating

A gradation of models/twins

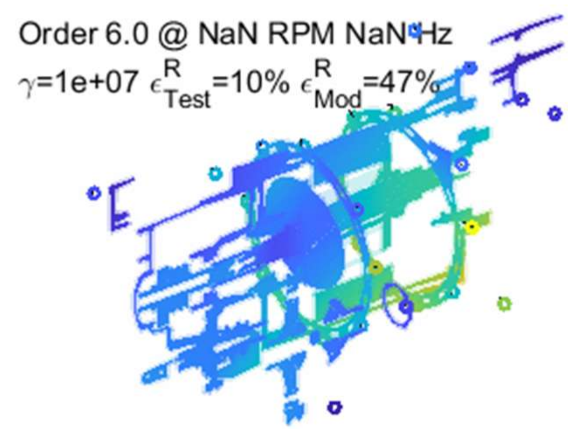
- Direct FEM simulation / virtual twin
  - Direct response, offline



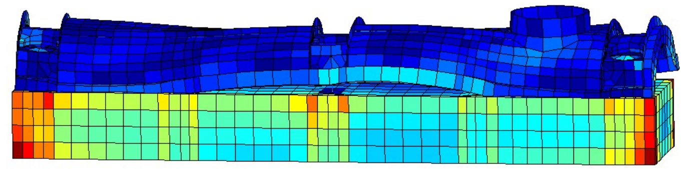
- Reduced-meta model / digital twin
  - Offline generation of training data
  - Reduction (direct problem)
    / learning (inverse, identification, training)
  - Online usage



- State-estimation, parameter updating / hybrid twin
  - Combine physical model & test



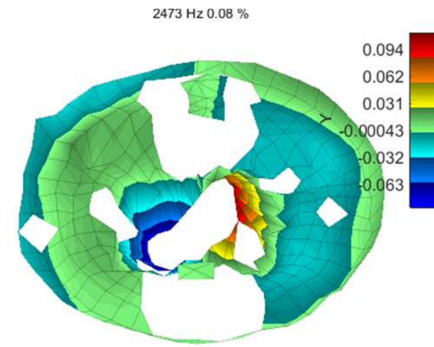
Lab work / evaluation



<u>Lab work</u> (with Mathieu Corus)

- 1 : code verification, signal, 1 DOF
- 2 : transfers, time/frequency
- 3 : identification, test/analysis correlation
- 4 : reduction and parametric models, updating

TP2-4 MATLAB +SDT : www.sdtools.com/sdtcur



<u>Evaluation</u>

- oral (PPT no interactive MATLAB), 30 mn (< 20 slides)
  equal weight for 1-2-3-4 (address most questions)
- <u>Work as pairs (not 3)</u>
- Evaluation on how you expose & comment results
  (5 pt per lab)

Data : http://savoir.ensam.eu/moodle/course/view.php?id=1874

⚠ MATLAB 2025a has incompatibilities, use 2024b or earlier

2025 Planning

- 9/9 Course1 : Intro, 1DOF, system
  C2 : modes & synthesis, base of reduction, spectral decomposition
- 16/9 C3 : signal for vibration (continuous vs. discrete, aliasing, windowing)
  C4 : Ritz and learning. Historical : McNeal, Craig-Bampton, …
- 23/09 Lab1 : 1 DOF, state-space, signal, NL
- 30/09 C5 : experimental modal analysis : from test to a system model. Inverse problem.
  C6 : Model parameterization, sensitivity computations
- 07/10 C7 : Reduction for reanalysis. Validity and error control.
- C8: Test/analysis correlation. Topology correlation. Observation, MAC, expansion. Start of model updating.
- 14/10 Lab2 : modal base frequency domain, transfers, transient, signal processing
- 21/10 C9 : damping : devices, physical mechanisms, numeric tools
  C10 : CMS (Component Mode Synthesis), coupling models, reduction for coupling
- 04/11 : Lab3 : identification, sub-space, test/analysis
  18/11 : Lab4 : Parametric models, reduction, damping, updating
- 25/11 : C11-12 subspace methods, current issues with non-linear systems, updating

17/12 : Oral

http://savoir.ensam.eu/moodle/course/view.php?id=1874

To go further

Course material (notes, slides)

https://savoir.ensam.eu/moodle/mod/folder/view.php?id=19444

For experimental modal analysis

[1] W. Heylen, S. Lammens, and P. Sas, Modal Analysis Theory and Testing. KUL Press, Leuven, Belgium, 1997.

[2] D. Ewins, Modal Testing: Theory and Practice. John Wiley and Sons, Inc., New York, NY, 1984.

[3] https://www.uml.edu/Research/SDASL/Education/Modal-Space.aspx

[4] K. G. McConnell, Vibration Testing. Theory and Practice. Wiley Interscience, New-York, 1995

Numerical aspects

[5] D. Inman, Engineering Vibration. Prentice-Hall, Englewood Clis, N.J., 1994.

[6] M. Geradin and D. Rixen, Mechanical Vibrations. Theory and Application to Structural Dynamics. Editions 1993 & 2015

[7] R. J. Craig and A. Kurdila, Fundamentals of Structural Dynamics. Wiley, 2006.

[8] https://www.code-aster.org : (English & French)

Keywords : 1 DOF / signal

After intro course: (chapter1 and section 2.1, modal.pdf)

1. Transfer (time, Fourier $i\omega$/Laplace s, asymptotic prop, NL)
2. Poles, resonance, damping ratio -3 dB method
3. State-space, poles
4. 1 DOF time exponential, convolution, logarithmic decrement
5. Strategies for transient in time & frequency
6. Equivalent power

Measurement and signal processing (CM3, signal.pdf)

1. DFT f_k, relation δt, T, δf, linearity, dilatation, (section 3.1)
2. Aliasing : Shannon's theorem, when, mitigate, … (s3.2.1)
3. Leakage & windowing : continuous vs. DFT (s3.2.2)
4. Transfer function estimate (H1, coherence) (s3.3)
5. Technology : sensors, actuators, acquisition

TP1 : code verification for 1DOF, integration, signal

Keywords : modes & synthesis, reduction

Modes & synthesis (CM2, see also second part of Modal.pdf slides)

1. Inputs/outputs, IO shape matrix, disp, resultants, … (s2.1)
2. Discrete modes (harmonic solution without input), orthogonality (section 2.2.1)
3. Ritz/Galerkin principles
4. Ritz/modal coordinates, PPV, series & state-space, time/freq strategies
5. Modal & Rayleigh damping, modal damping in physical coord (s 2.2.x)
6. Peak visibility, truncation, effective contributions (s 2.2.x)

Reduction (course 4, see also Reduction.pdf slides)

1. Ritz/Galerkin & learning
2. Modes + Residual flexibility (section 4.3)
3. McNeal= Ritz with "residual vectors", pre-filter low frequency modes
4. Residual vectors in presence of flexible modes
5. Guyan, Craig-Bampton = enforced displacement & bandwidth (s 4.3.2)

Left for other course : from vector set to basis

Keywords : parametric models

Sensitivity / extended uses of modes (co. 5, SensitivityReanalysis.pdf)

1. Parametrization (s 9.1)
2. Sensitivity of static response, adjunct state (s 9.2)
3. Sensitivity of frequencies : relation with energy distribution (s 9.3)
4. Sens. of mode-shapes : modal crossing + numerical strategy for inverse of underdetermined problem

Parametric studies (course 6)

1. Reanalysis example in modal basis (start by continuous case of spring on tensioned wire). Generalization to ΔK.
2. Multi-model and nominal + residual methods
3. Illustrations (damping/updating)
4. Error control, iterative basis refinement
5. Orthogonalization strategies, GS/GSM/IGSM, Mseq

TP2 : modes & synthesis, signal

Keywords : experimental modal analysis

Identification (course 7, EMA.pdf)

1. Identification demo
2. Inverse problems : model forms, data (s 6.1)
3. Model forms for identification, discussion of residual terms
4. Frequency domain least-squares solution, implicit NL
5. Evaluation of results (ch 7)

Test/analysis correlation (course 8, Correlation.pdf)

1. Topology correlation (s 8.1)
2. Measuring distance between test & analysis. Shape correlation : MAC, pairing issues (s 8.2)
3. Static condensation/expansion, reduced mass, orthogonality on sensors (s 8.3)
4. Hybrid models

Current trends 1

Damping (course 9, damping.pdf)

1. Sample damping devices
2. Notion of coupling & impact on damping
3. Viscoelasticity/complex modulus, MSE
4. Real modes/modal damping & separation complex modes & enhanced reduction
5. Internal states (// with friction)

Substructuring (Component mode synthesis) (course 10)

1. Coupling conditions : energy or continuity
2. constraints : elimination, Lagrange, Penalization
3. contact & locking/stress concentration
4. Reduction for CMS : classical Craig-Bampton, CMT
5. The "problem" of large interfaces

TP3 : parametric models, damping, identification, correlation

Current trends 2

Updating (course 11, updating.pdf)

1. Typical errors : property, geometry, contact, model
2. Physical and equivalent models
3. Least squares and conditioning, SVD (link with TP3)
4. Error localization
5. Sample applications

Features in vibration behavior (course 12)

1. SVD for mechanics : principal loads, modal energy coordinates, interface DOFs
2. Modal coordinates, physical and macro-models models of junctions with contact/friction
3. Geometrically periodic systems (engine, track)