Vibrations des structures

https://savoir.ensam.eu/moodle/course/view.php?id=11767

PA1 (S1) - Prototypage virtuel
2024 PA1 (S1) Modelisation des systemes en dynamique

Etienne Balmes,
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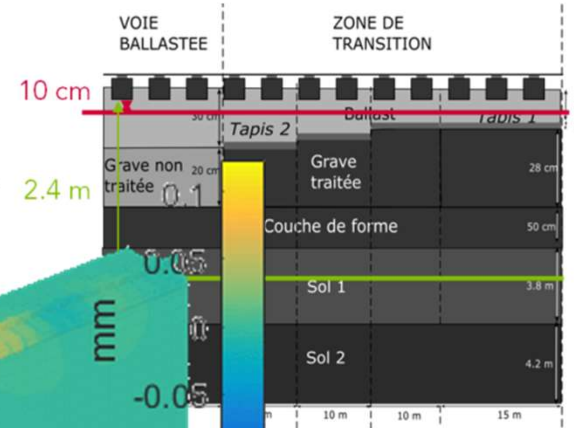
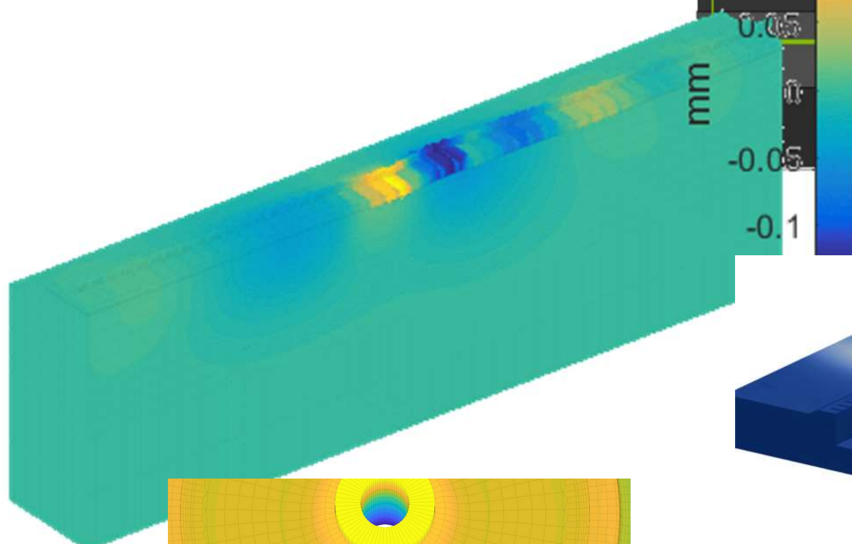
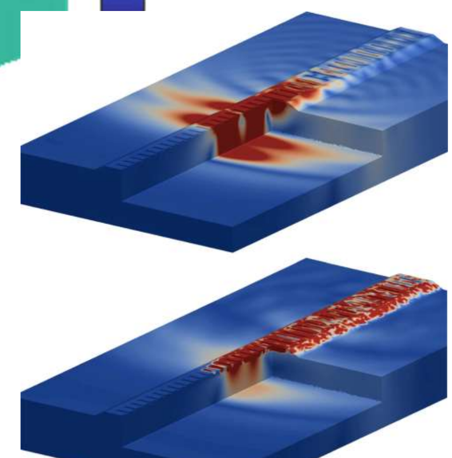
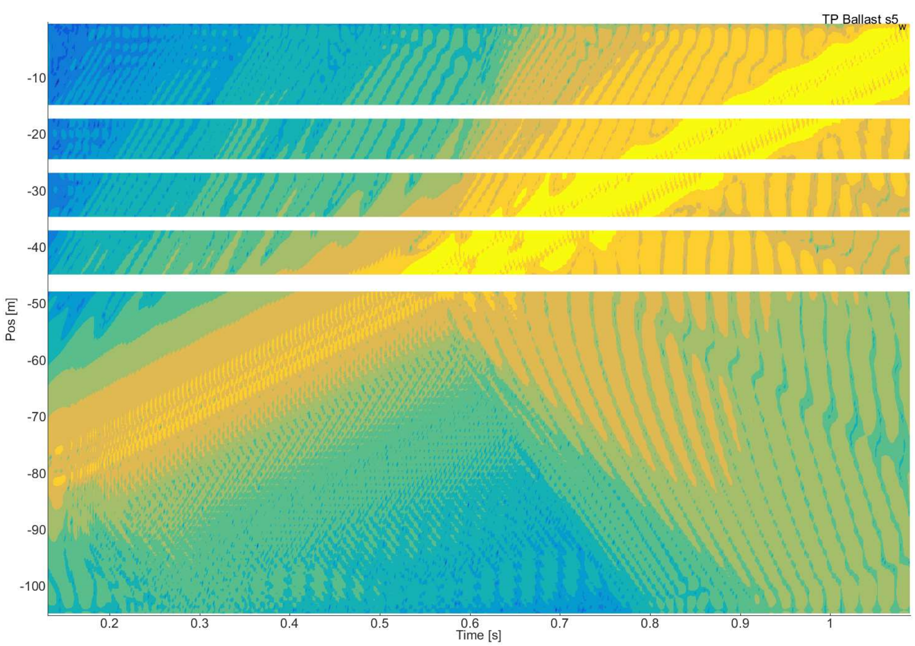
Track/train interaction

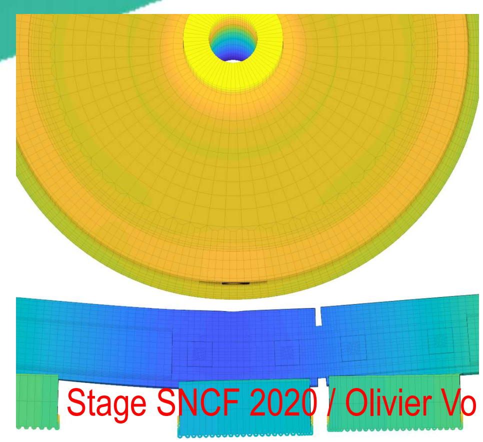
- Piece-wise periodic structure with 15e3 node per 60cm slice
  - Full 3D > 5h, 90 Gb
  - Reduced 23 min, 100 Mb
- Scientific issues
  - model reduction, wave propagation, random properties of ballast
  - Rail/wheel contact, fatique











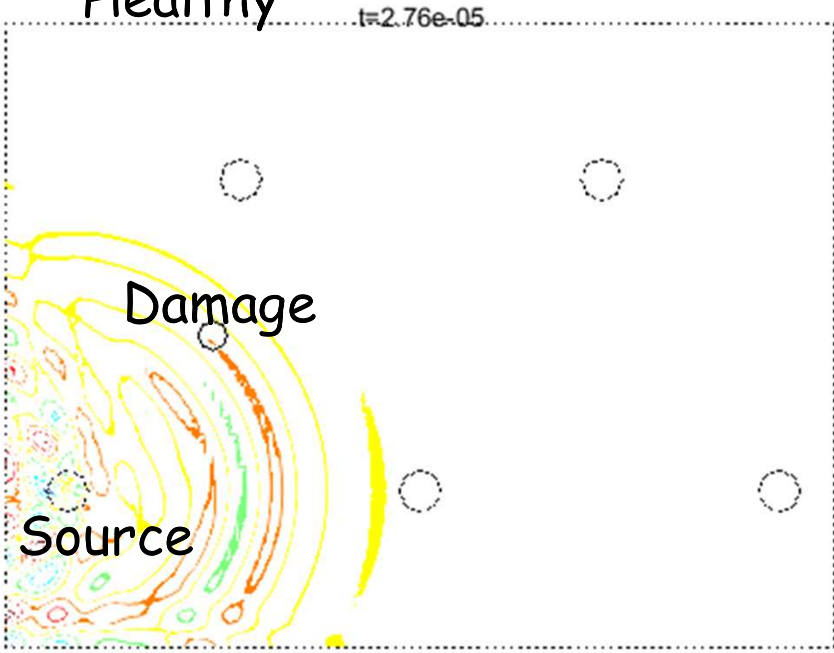
Ph.D. Elodie Arlaud (2014-16), Hadrien Pinault (2017-)

Stage SNCF 2020 / Olivier Vo Van

Lucio de Abreu Corrêa & al.

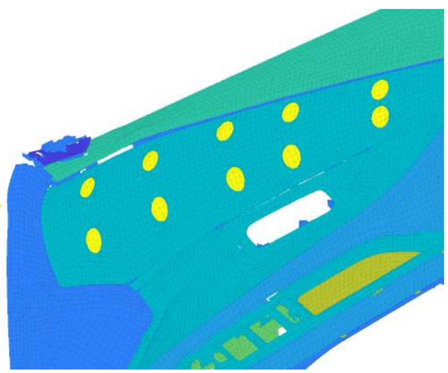
SHM transients

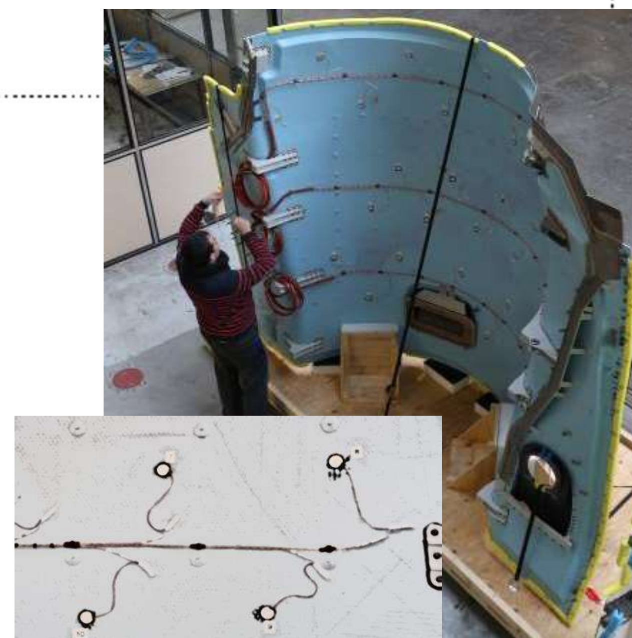
Healthy



Damaged-healthy

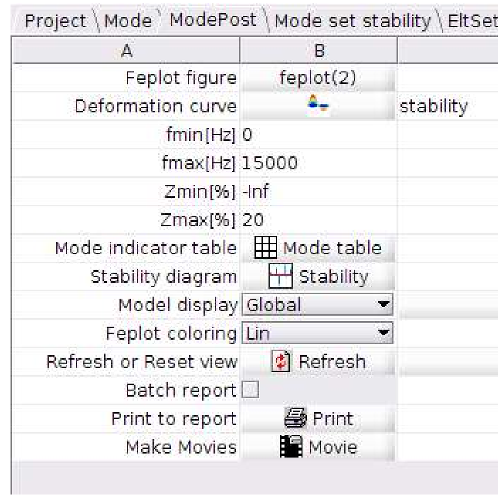
- Electrical signals used for measurement
- Damage acts as a source in healthy-damaged signal



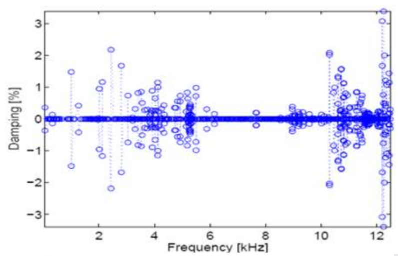


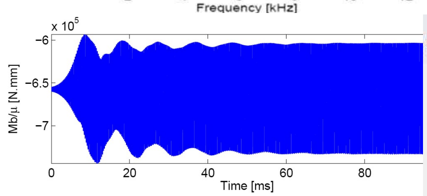
Brake squeal simulation

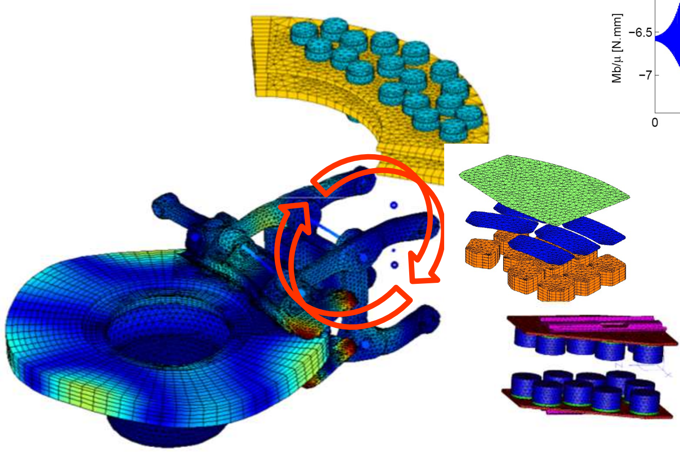
- 1 full time @ SDTools (Audi, Daimler, PSA, CBI, …)
- Advanced solvers in frequency & time
- Objectives
  - Industrial design tools
  - Parametric model reduction
  - Optimized transients

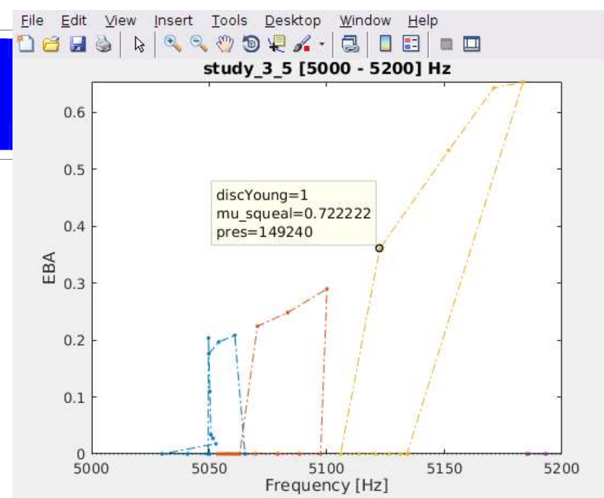


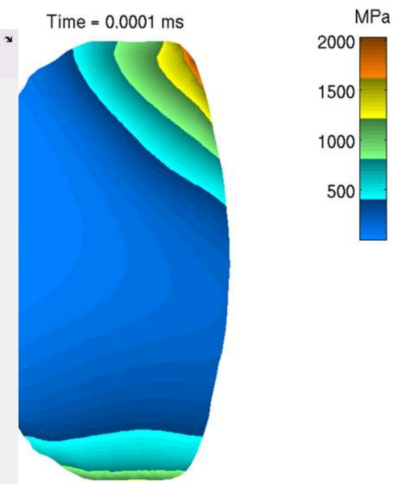
Freq	Damp	SqC	EBA	VNSD
1290	0.01%	-0.02	0E0	8.1
1455	0.01%	-0.01	0E0	8.1
1519	0.24%	-0.48	0E0	5.9
1991	0.07%	-0.15	0E0	7.2
2220	0.03%	-0.07	0E0	7.6
3325	0.03%	-0.06	0E0	7.4
3441	0.05%	-0.11	0E0	6.7
5050	-0.02%	0.05	1.751E-1	5.6
5058	0.76%	-1.52	0E0	2.
5134	0.85%	-1.70	0E0	5.5
5281	0.19%	-0.39	0E0	5.2
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









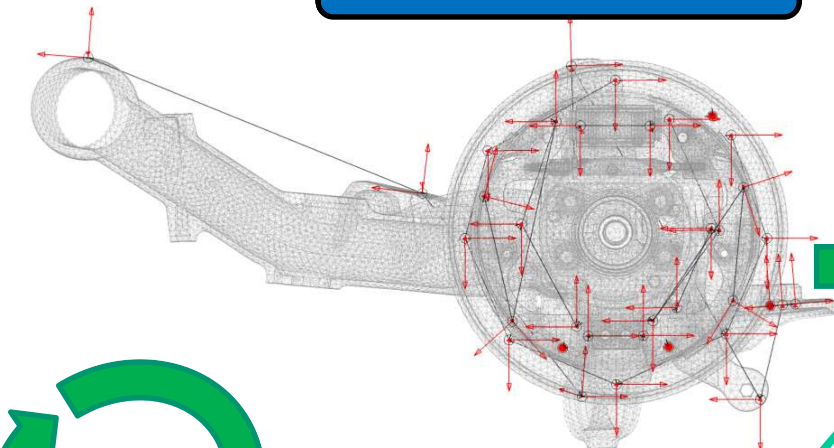


Squeal testing : combined test/FEM

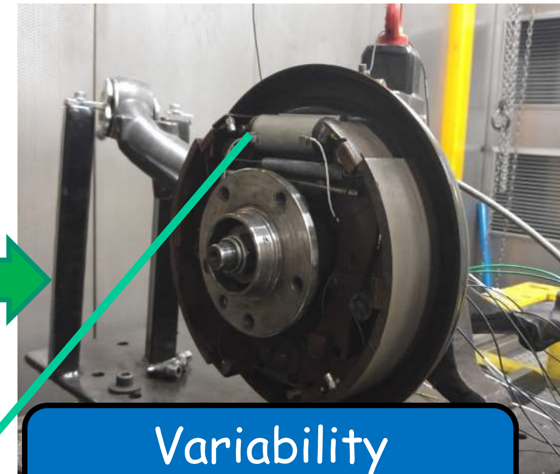
Full FEM

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

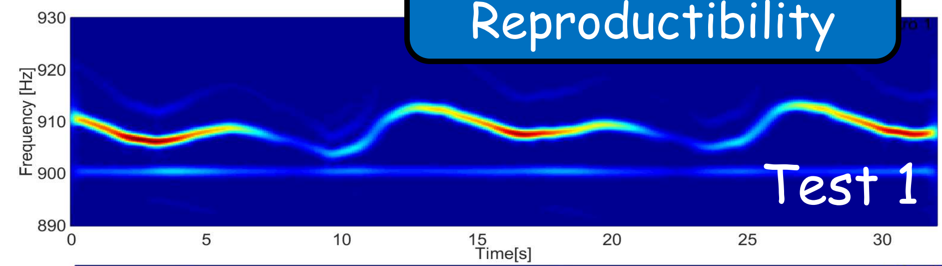
Sensor placement

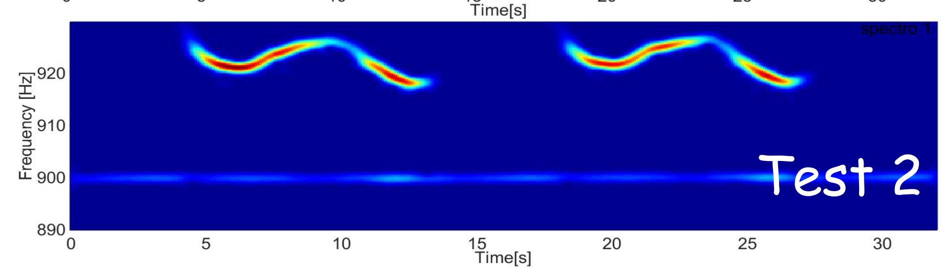


Real test

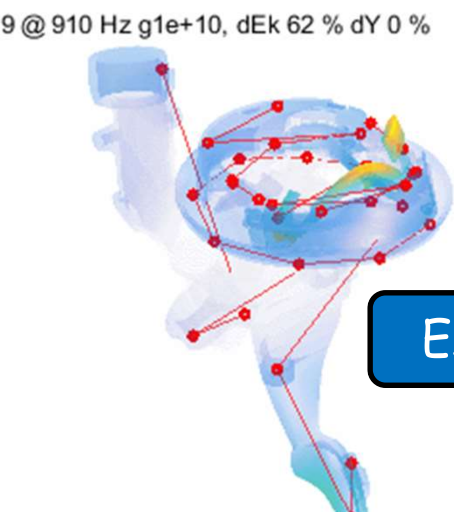


Variability
Reproductibility

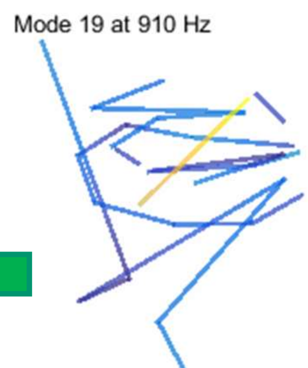




Squeal : time varying with wheel position



Expansion

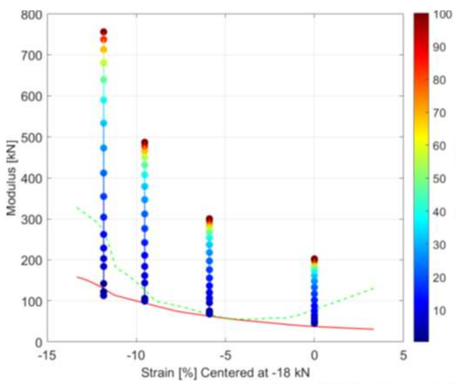


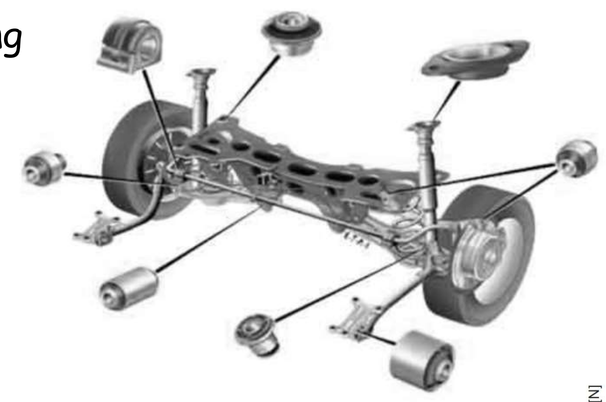
Shape extraction

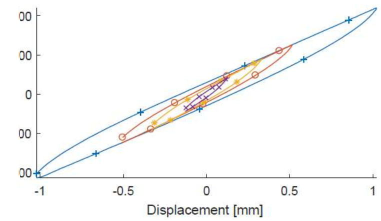
Viscoelastic damping

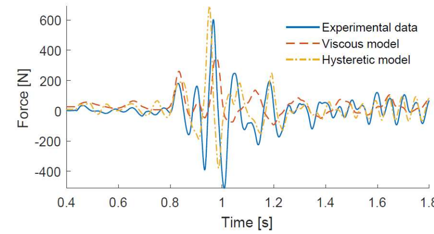
Scientific problems with damping

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

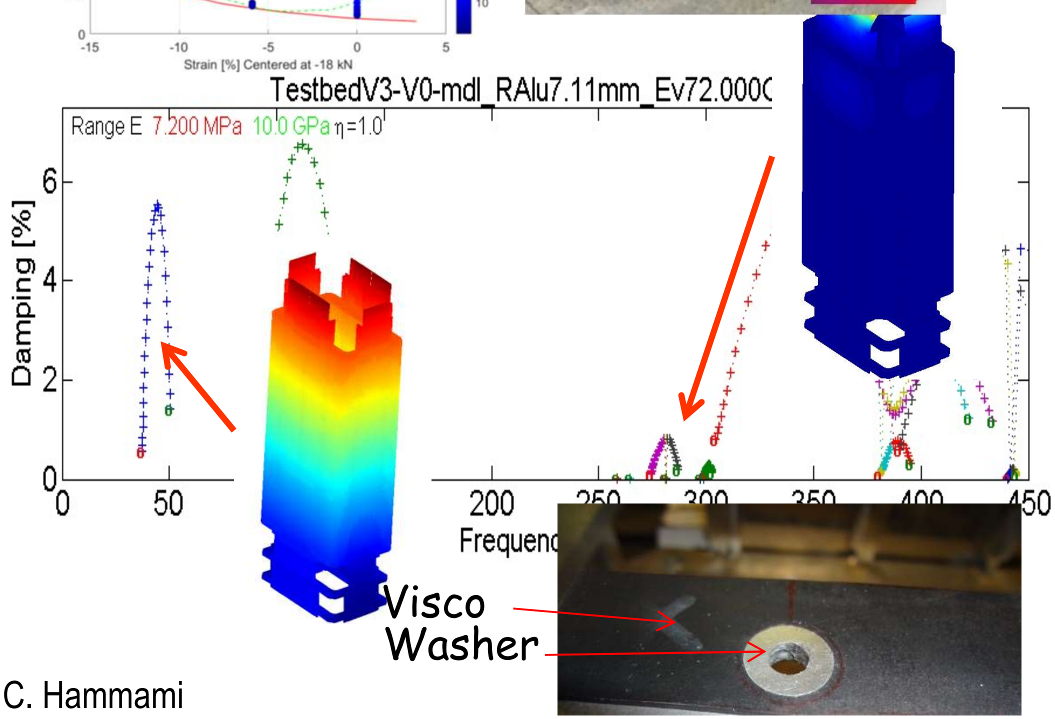




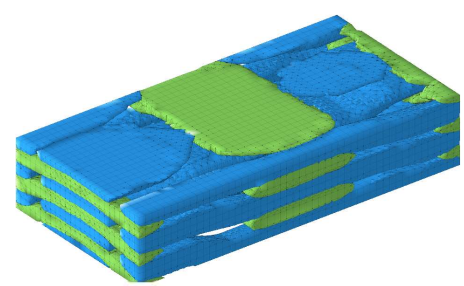




Ph.D. R. Penas 21



Ph.D. C. Hammami



Ph.D. F. Conejos 21

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

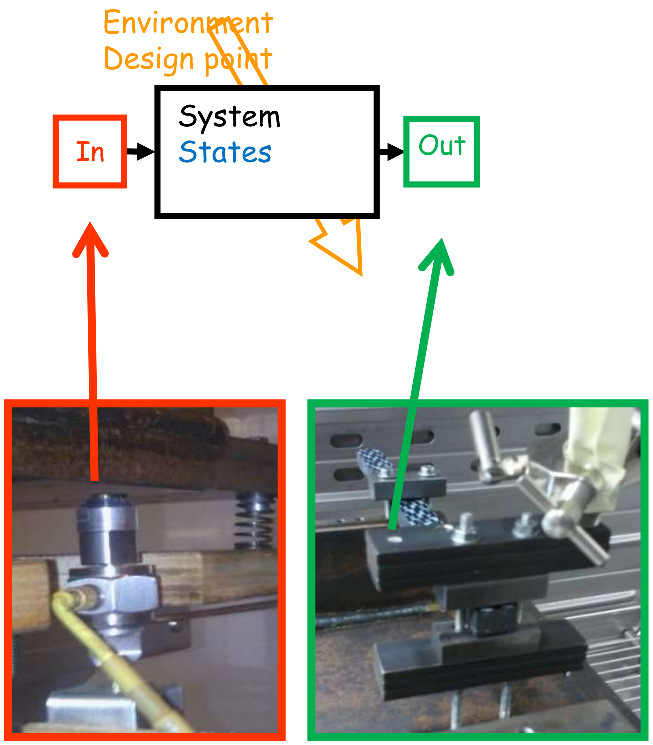
CAD/Meshing
FEM
Simulation
Testing

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 ?



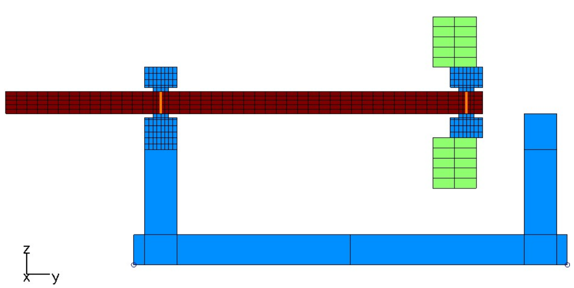
- **Inputs $u(t)$** : hammer with force measurement
- **Outputs $y(t)$**
  - Test : vibrometer on testbed
  - Computation : stresses
- **State $x(t)$**
  - Displacement & velocity field as function of time

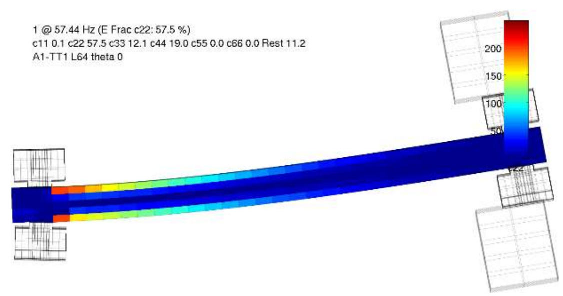
$$\{\dot{x}(t)\} = f(x(t), u(t), p, t) \qquad \text{evolution}$$

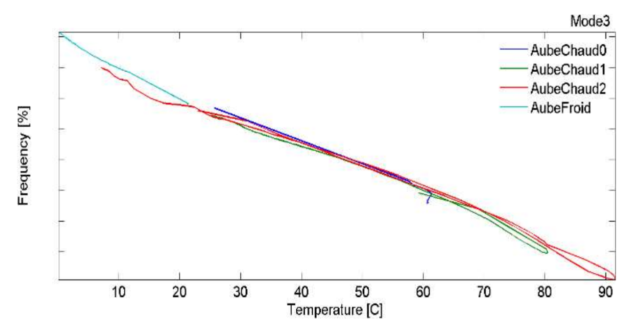
$$\{y(t)\} = g(x(t), u(t), p, t) \qquad \text{observation}$$

- **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)

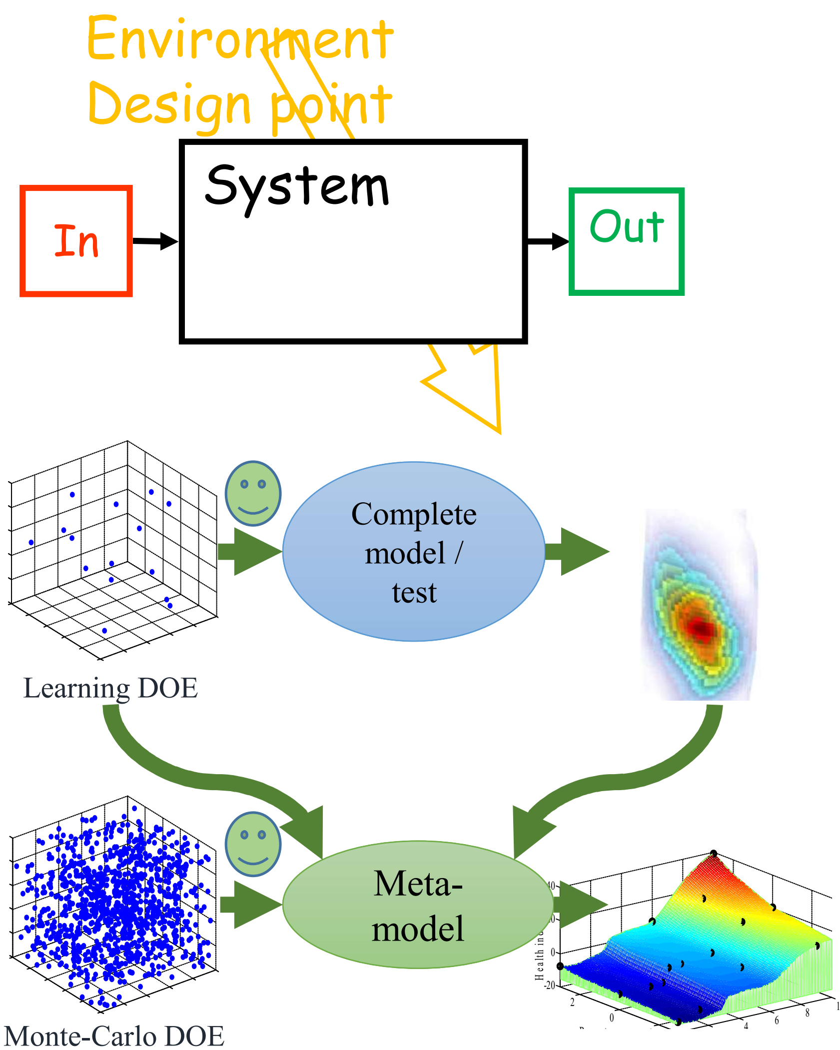






Simple example : modified Oberst test for 3D weaved composite test

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

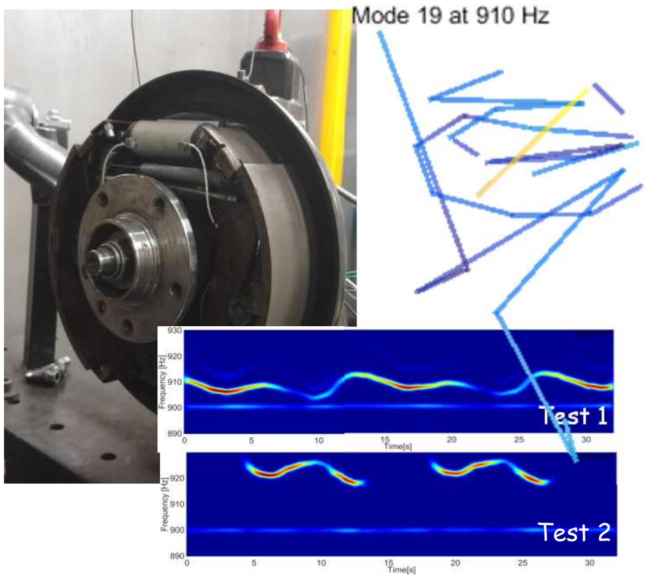
Certify

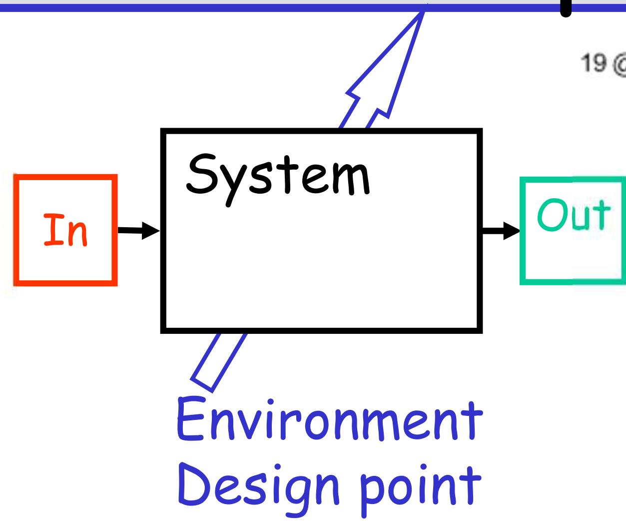
- Optimize tests : number, conditions
- Understand relation between real conditions and certification
- Account for variability

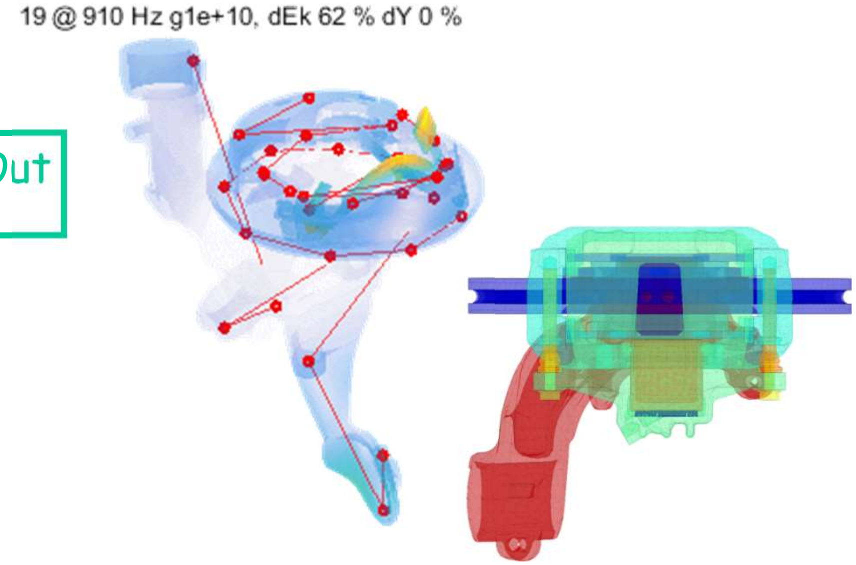
Maintain during life

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

A system = I/O representation







Prototype

Virtual prototype

- ☺ all physics (no risk on validity)
- ☺ in operation response
- ☹ limited test inputs
- ☹ measurements only
- ☹ few designs

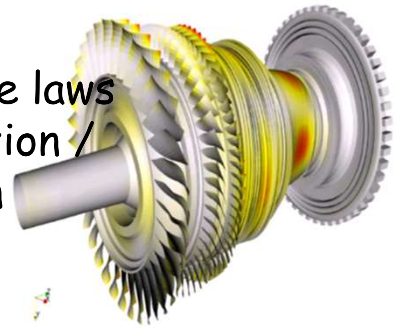
- 😐 Cost : build and operate

- ☹ limited physics (unknown & long CPU)
- ☹ design loads
- ☺ user chosen loads
- ☺ all states known
- ☺ multiple (but 1 hour, 1 night, several days, … thresholds)
- 😐 Cost : setup, manipulate

FEM model / system model

σ(x,t)
f(x,t)

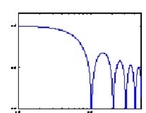
- Geometry
- Constitutive laws
- Discretization / idealization



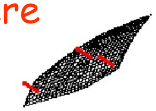
u(x,t)
σ(x,t)

Extensions : coupled, time variant, non-linear, …

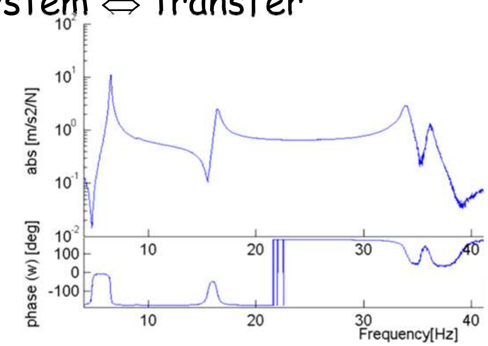
When



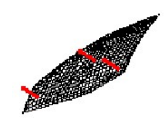
Where



Assumption : linear time invariant
System ⇔ transfer



Sensors

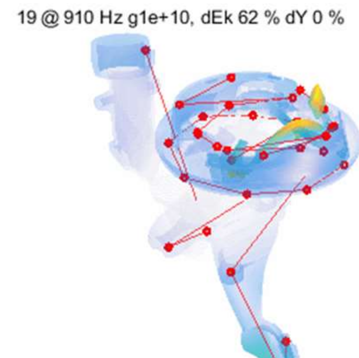


Extensions
- Coupling (structure, fluid, control, multi-body, …)
- Optimization, variability, damping, non linearity, …

Model validation and verification

CAD Model

Experimental model



Continuous model +interfaces

$$\text{On } \Omega \quad \mathrm{div}\sigma + F_v = \rho\ddot{u}$$

$$\text{On } \partial\Omega \quad u(x,t) = u_{given}$$

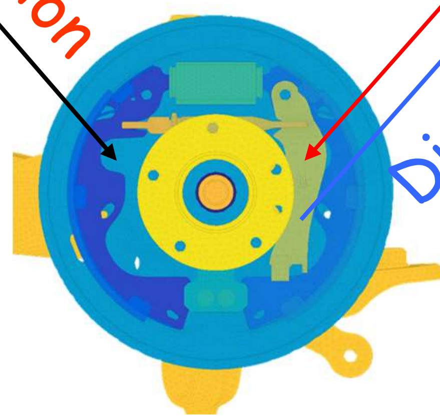
$$\{T\} = [\sigma]\{n\}$$

Verification

Design

Validation (Updating)

Dispersion



FE/numerical model

1990 : model updating
2000 : virtual prototype
2019 : digital twin

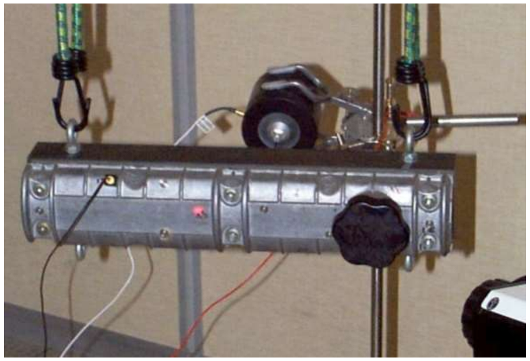
Lab work / evaluation

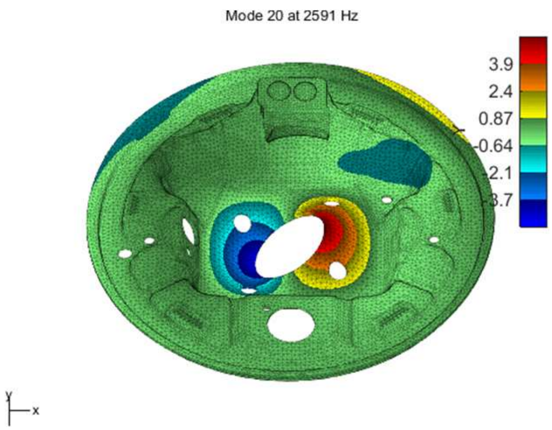
Objectives :

- understand key notions by application on your own
- Be able to describe results properly
- Evaluation : 30 mn + 10mn questions per group
  oral presentation (ppt)

Topics

- One DOF simulation, FFT
- Transfer function simulation
  - frequency (observability, commandability, damping)
  - Time (aliasing, modal truncation, …)
- Experimental modal test
  - Analyze identification
  - Analyze correlation
- Design problem
  - Use parameters to avoid frequency and optimize response





Dates 2023

- 27/9 13:00 CM12 : intro, modal, CM3 modal,
- 04/10 13:00 : CM4 signal CM5 reduction
- 11/10 13:00 : TP1 1 DOF
- 19/10 8:00 : CM 5 identification, CM6 test/analysis correlation
- 25/10 13:00 : TP 2 : frequency response, time response
- 06/11 13:00 : CM 78 : sensitivity, parametric studies/updating
- 15/11 13:00 : TP 3 identification, parametric
- 06/12 14:40 : CM 910 : sub-structuring/damping

23/12 Oraux

Keywords on topic : 1 DOF

After intro course: (chap.1, sec 2.1, course 1, also modal.pdf)

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

Measurement and signal processing (course 2, signal_test.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 (course 3, see also second part of Modal.pdf slides)

1. Inputs/outputs, IO shape matrix, disp, resultants, … (s2.1)
2. Discrete modes (harmonic sol. 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

TP2 : modes & synthesis, signal

Keywords : experimental modal analysis

Identification (course 5, Identification_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
5. Evaluation of results

Test/analysis correlation (course 6, correlation.pdf)
1. Topology correlation (s 8.1)
2. Measuring distance between test & analysis. Shape correlation : MAC (s 8.2)
3. Static condensation/expansion, reduced mass, orthogonality on sensors (s 8.5)

Keywords : parametric models

Reanalysis/sensitivity= extend use of bases (course 7, ch 9)

1. Reanalysis example in modal basis (can start by continuous case of spring on tensioned wire). Generalization to ΔK.
2. Sensitivity of frequencies : relation with energy distribution. (s 9.3)
3. Sens. of mode-shapes : modal crossing + numerical strategy

Parametric studies (course 8)

1. Updating : principles, parameter choices
2. Parametrization, reanalysis, meta-models
3. Freq/MAC updating, generic NL least-squares, sensitivity scaling
4. First order correction (damping illustration)
5. Eigenvalue computations

TP3 : parametric models, damping, identification, correlation

Keywords : current trends

Damping (course 9)

1. Sample damping devices
2. Notion of coupling & impact on damping
3. Physical mechanisms : friction, viscoelasticity, coupling, non-linearity
4. Viscoelasticity/complex modulus, MSE, Rayleigh modal damping
5. Real modes/modal damping & separation
   complex modes & enhanced reduction
6. Internal states (// with friction)

Subspace methods (course 10)

1. Substructuring
2. From vector sets to bases, SVD & analysis