Updating

- Principles
- Matrix or parameter updating
- Objective function summary
- Parameter selection
- Optimization tools

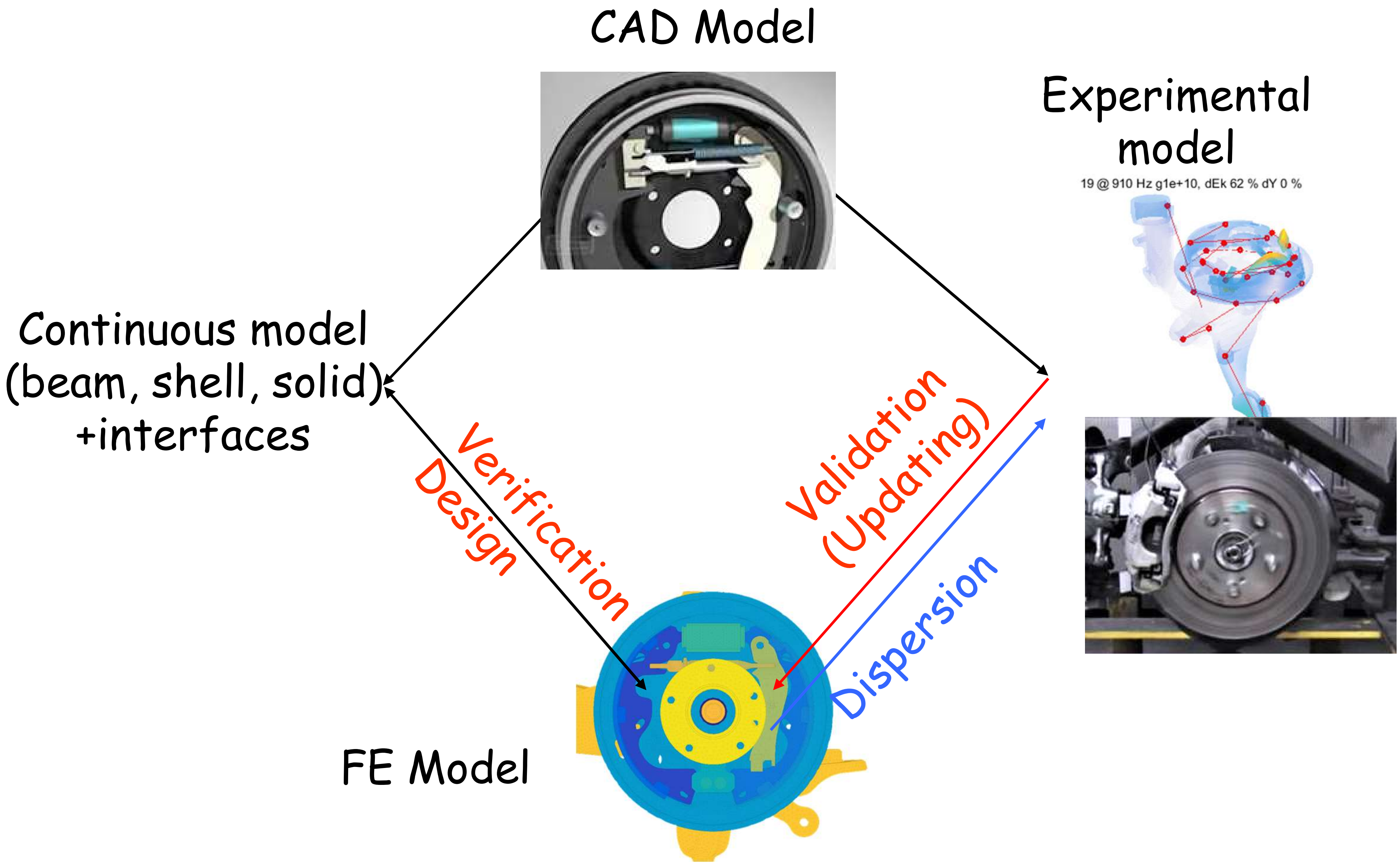
SDTools VIBRATION SOFTWARE & CONSULTING

Arts et Métiers Institute of Technology

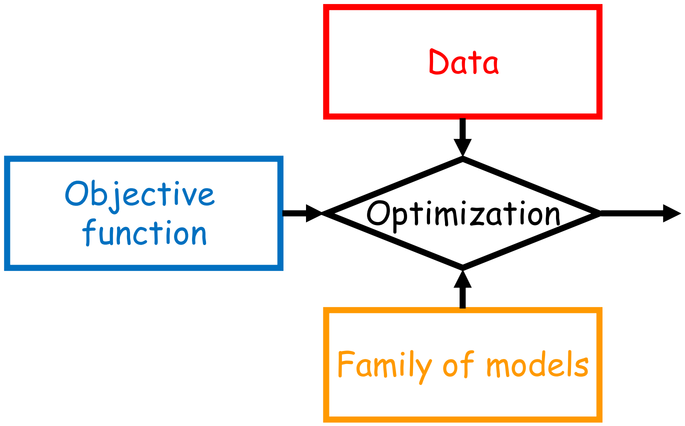
MS2SC http://savoir.ensam.eu/moodle/course/view.php?id=1874

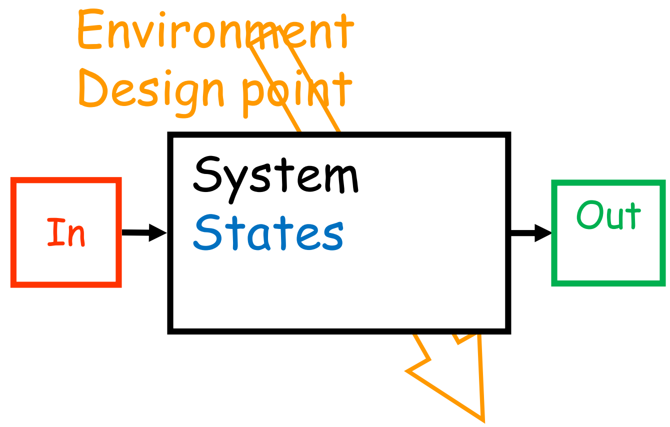
PROVIR http://savoir.ensam.eu/moodle/course/view.php?id=490

Model validation and verification



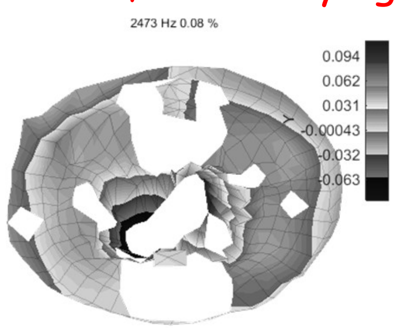
Parametric inverse problems





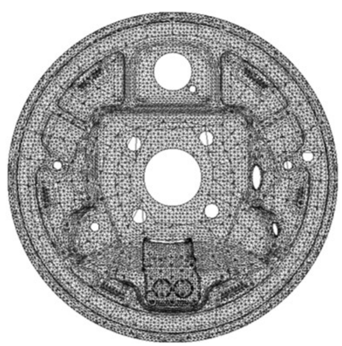
Identification error

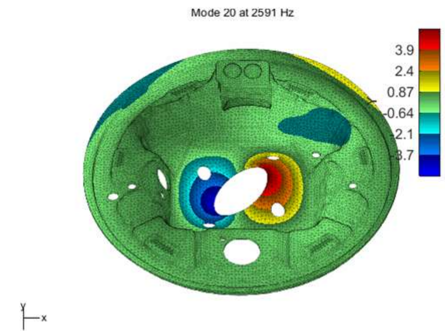
- Noisy measurements
- Identification bias
- NL, time varying, …



Topology errors

- sensor/act position
- matching



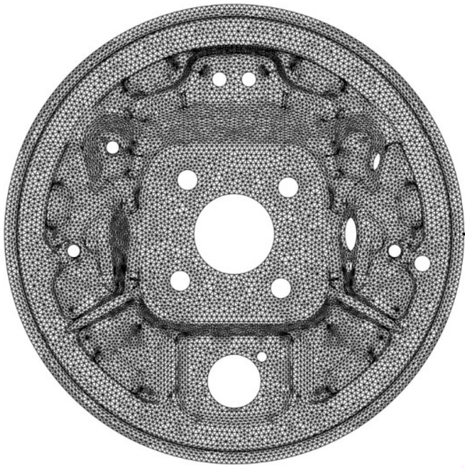


FEM error

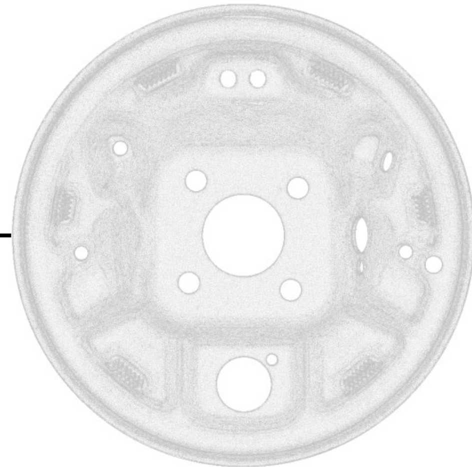
- Geometry
- Material parameters
- Multi-scale problems & equivalent parameters
- Junction representation
- Design change & modal property tracking

Geometry updating

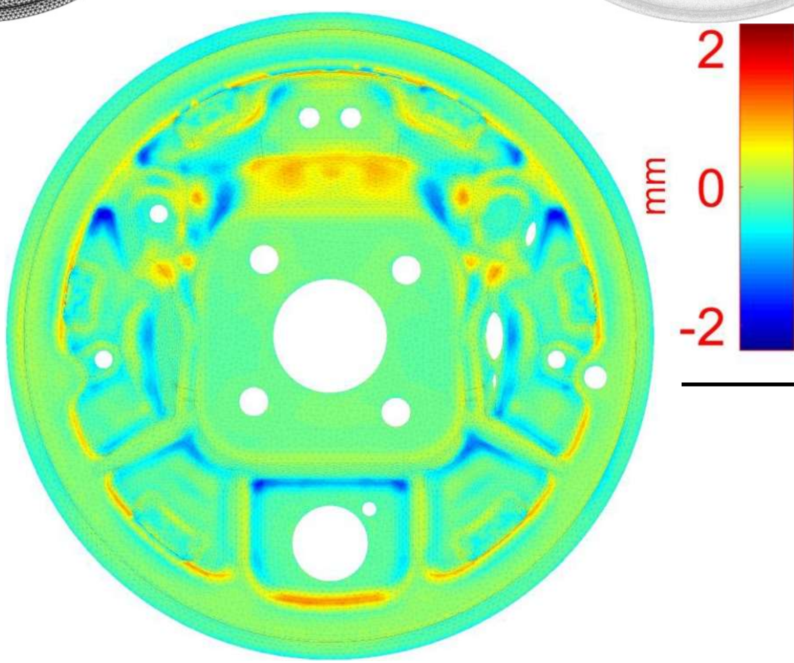
Nominal geometry



Measured geometry

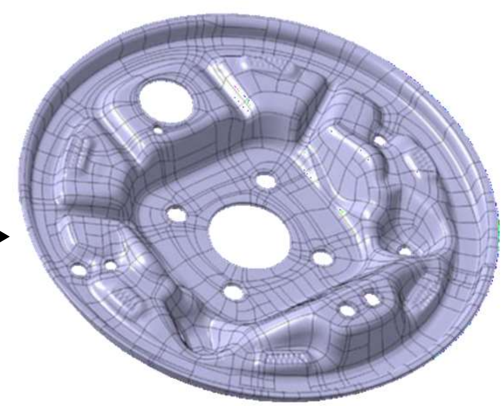


- Up to 2 mm on surface
- 11% error on volume



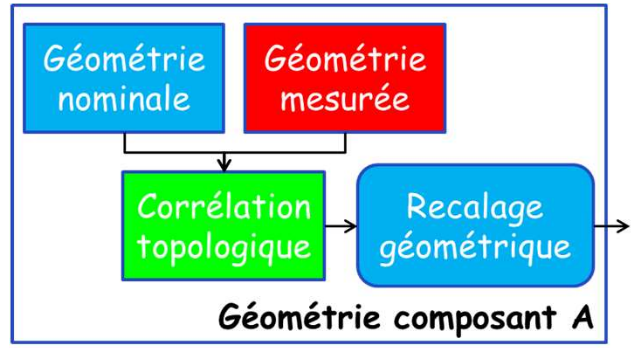
Geometry correlation

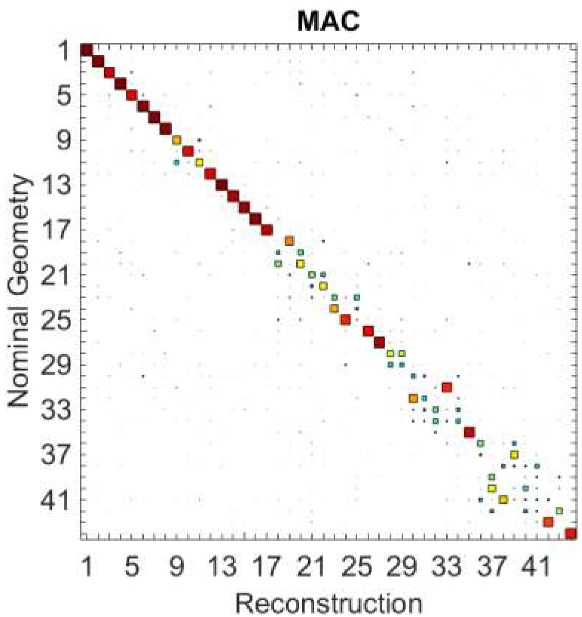
Inverse CAD
(Geomagic, …)
Morphing (SDT)

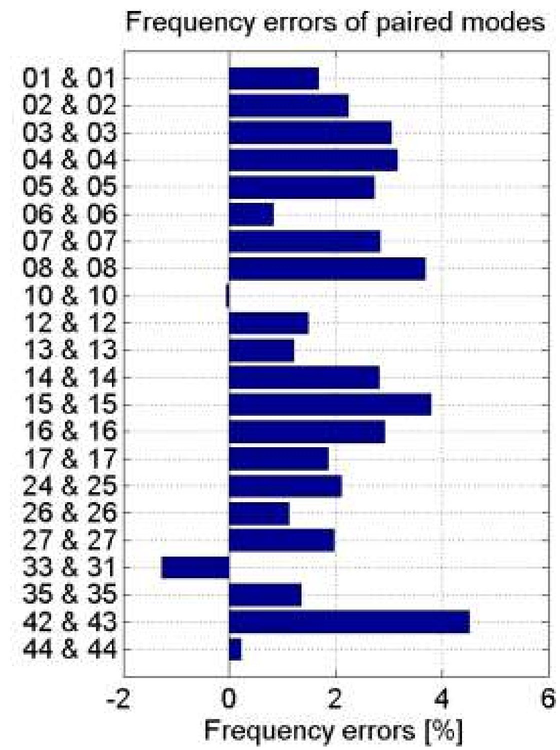


Geometry updating

- Frequency band : 0 – 6kHz
- Notable shape difference >3 kHz
- Frequency error
  - 2 % mean
  - 5 % max



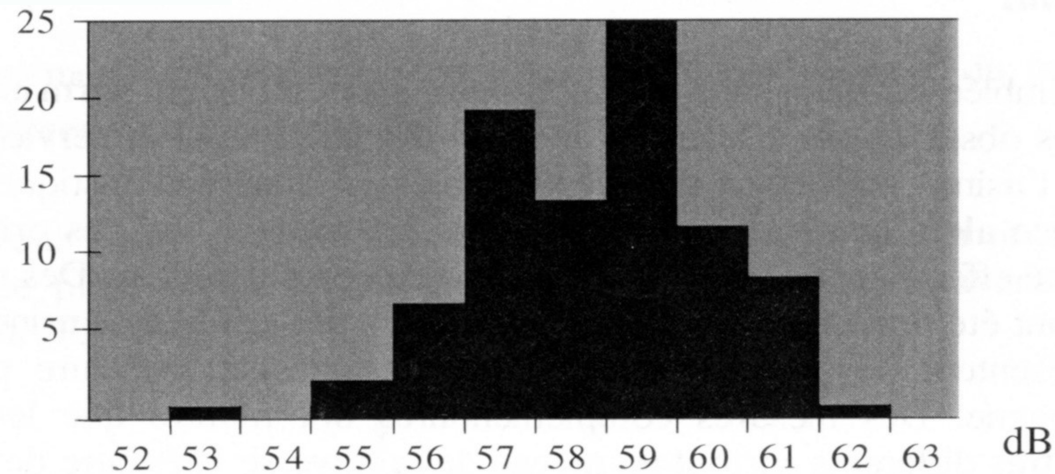




- Checking geometry should always be the first step
- Shells strong effect of geometry errors ≈ thickness

Invariance : influence of object

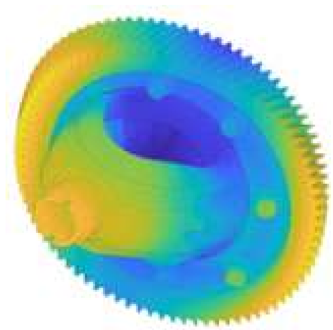
- Multiple measurements show significant variability



Spot welding manufacturing process has inherent variability due to

- Geometric tolerances
- Weld failure (several %)

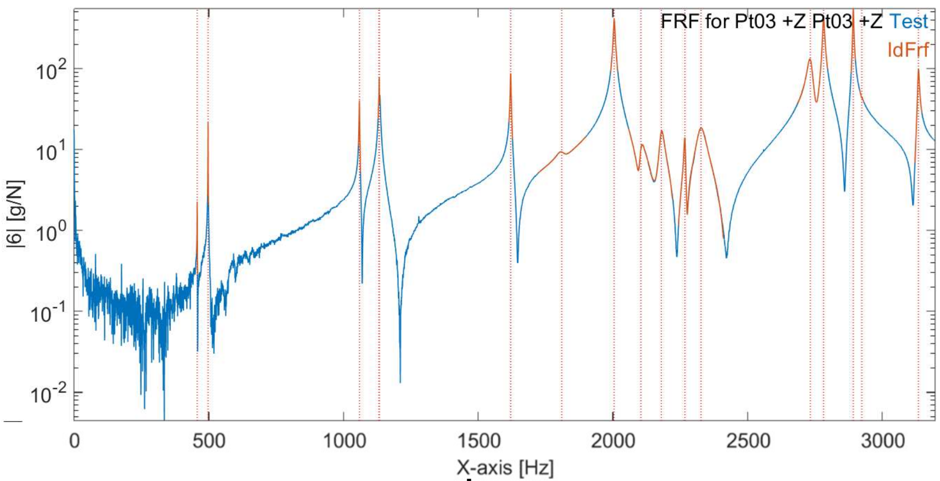
Gear have similar sensitivity to geometric tolerance



Updating of material properties

Modal frequencies

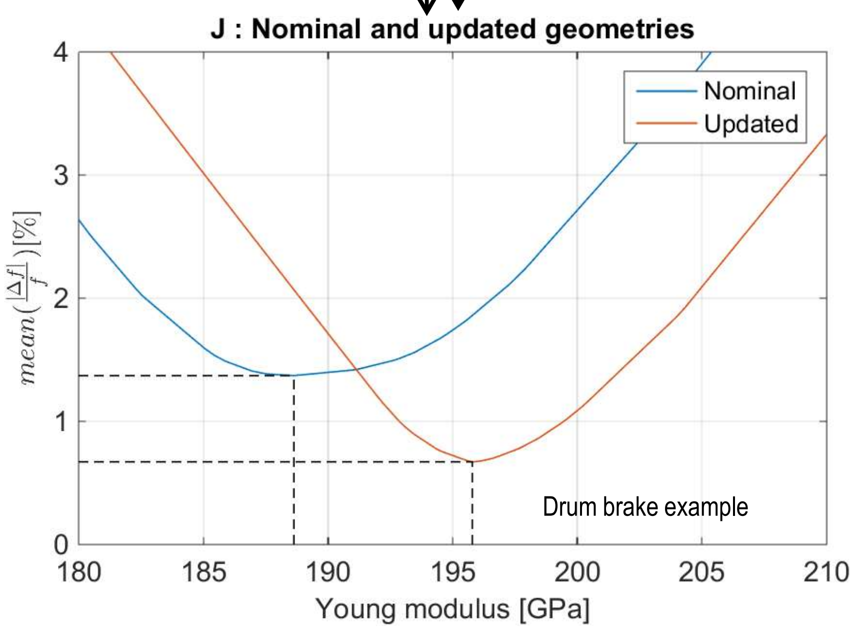
Weight



- Weight / volume ⇒ density
- Frequencies ⇒ modulus
- Test/FEM distance below physical dispersion (df/f≈2%)

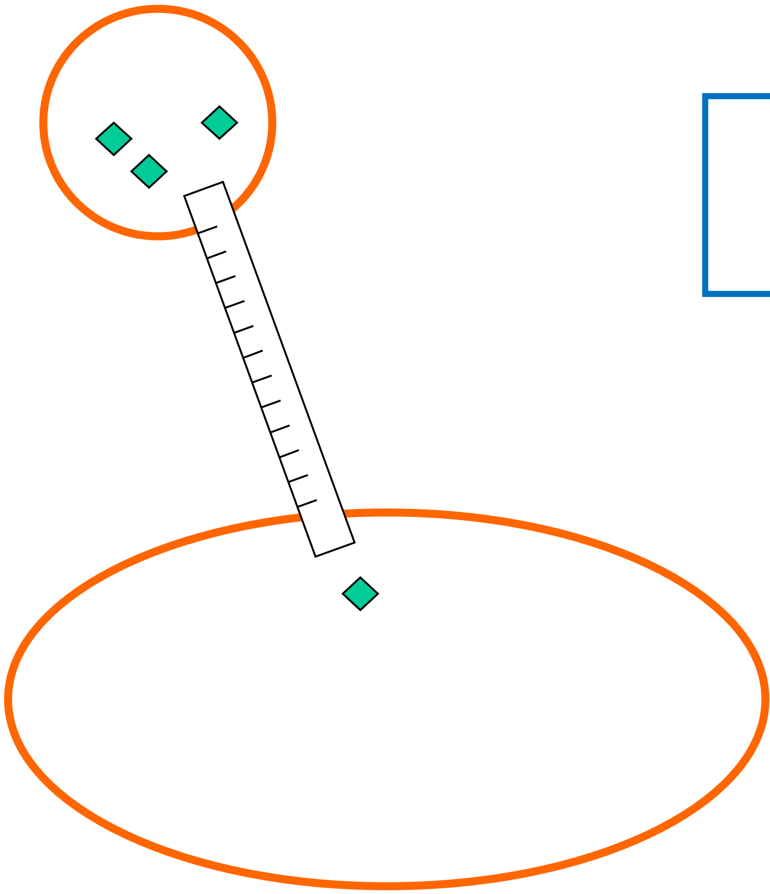
Frequency correlation

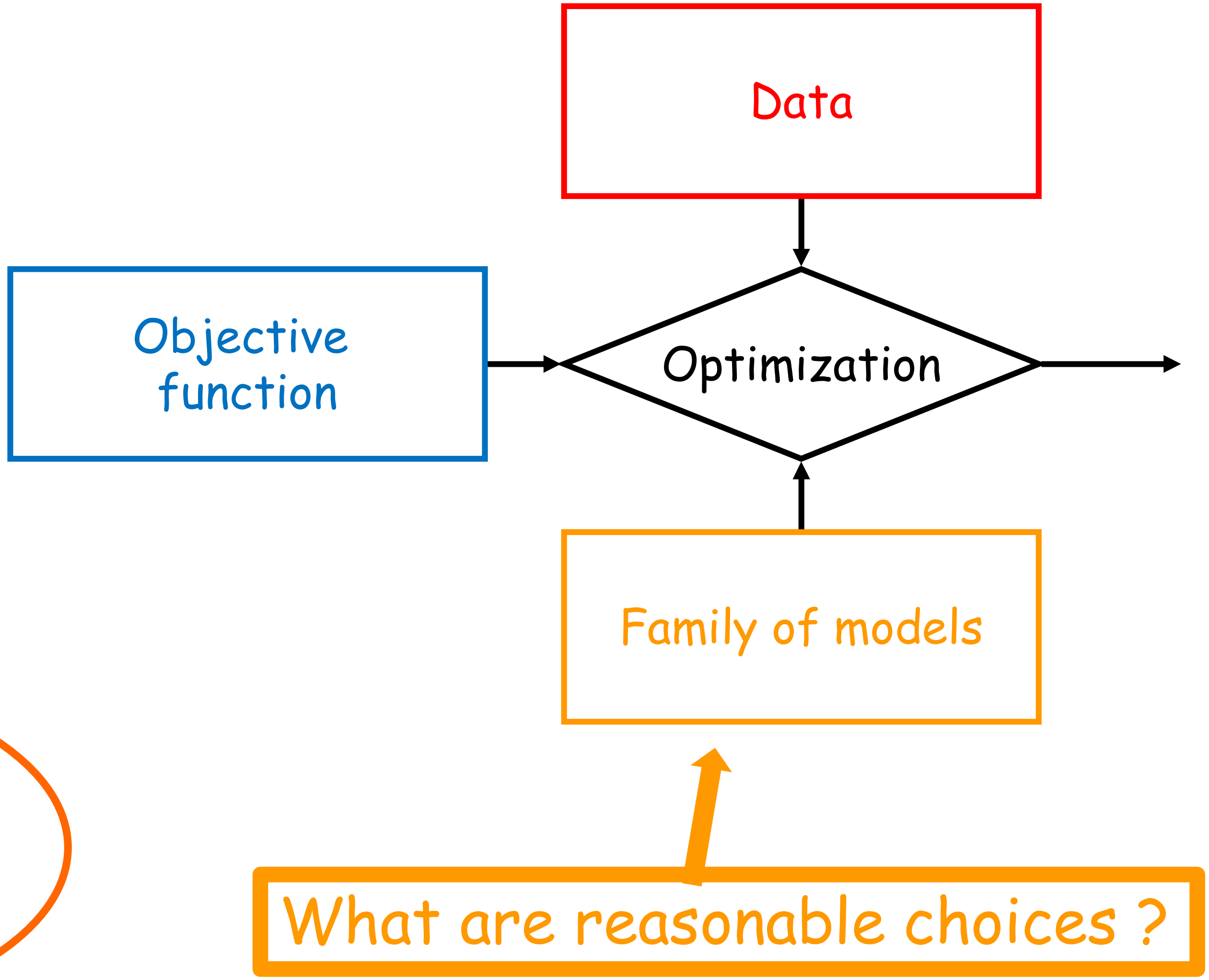
$$J = \min_E \left(\sum_i \frac{|\Delta f_i|}{f_i} \right)$$



Wrong volume = bias

Phase 2 : reasonable parameters





Equivalent materials / homogeneization

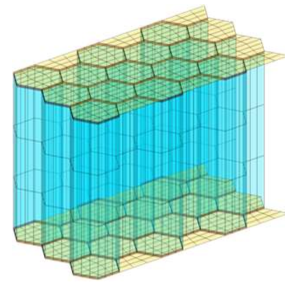
Family
- **Micro** : cell walls, glue, face-sheet, viscoelastic material
- **Macro** : shell/ orthotropic volume/ shell

Objective
- Equivalence: waves/modes

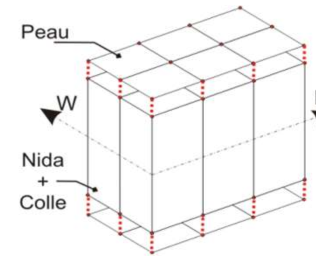
Parameters
- orthotropic law

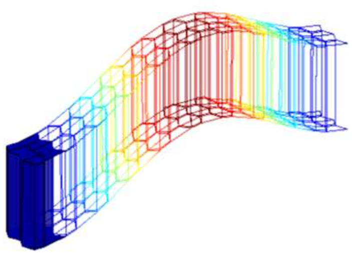
- Scale separation

Detailed 3D honeycomb

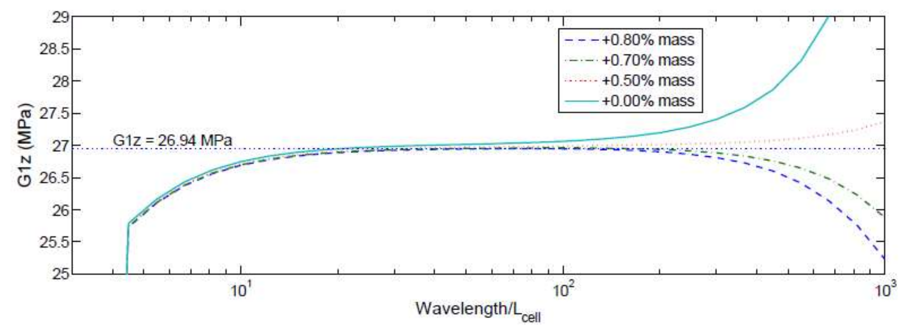


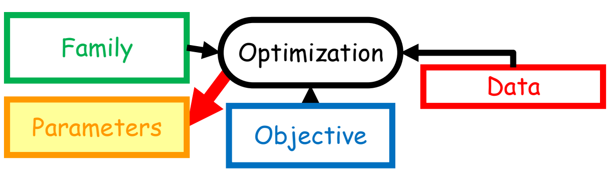
Shell/volume/shell



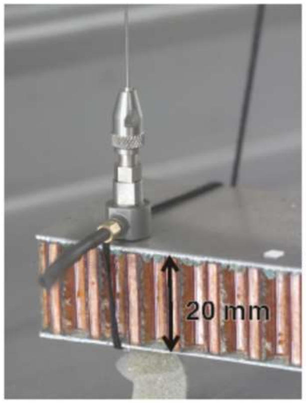


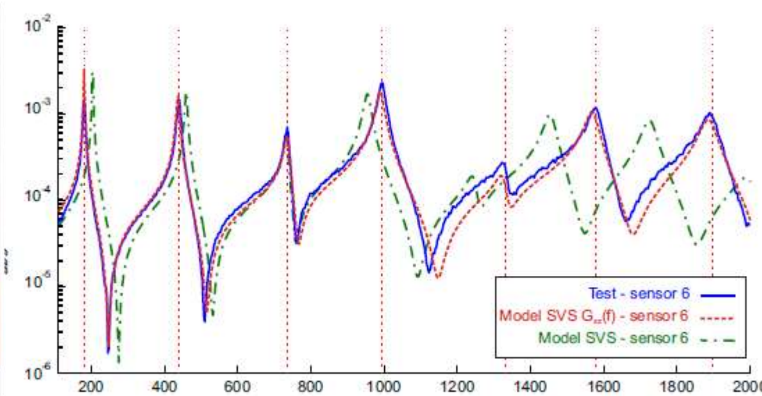
Numerical homogeneization





Updating from test

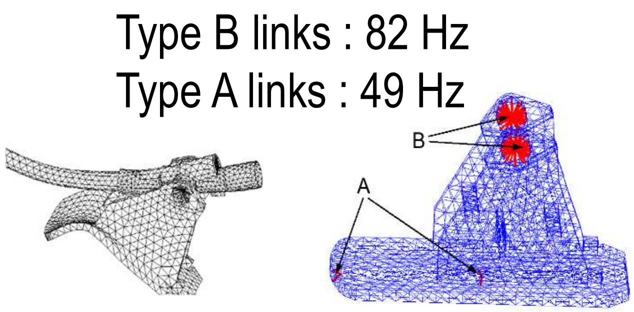


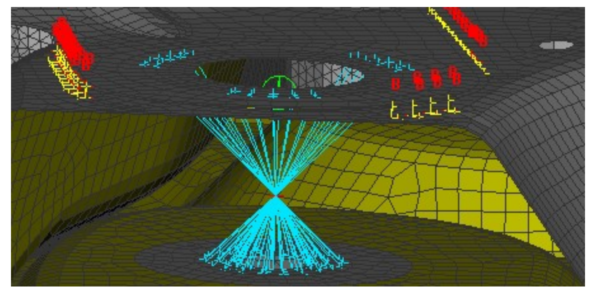


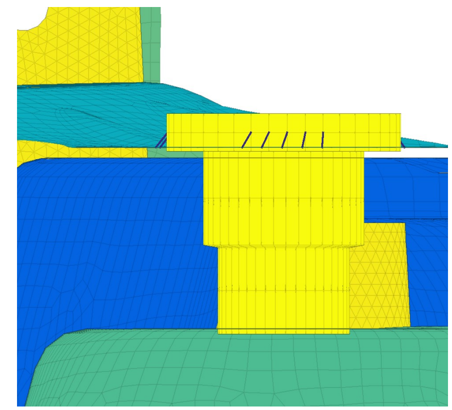
C. Florens, « Modeling of the viscoelastic honeycomb panel equipped with piezoelectric patches in view of vibroacoustic active control design », ECP, 2009.

Junctions : contact / 0D strategies

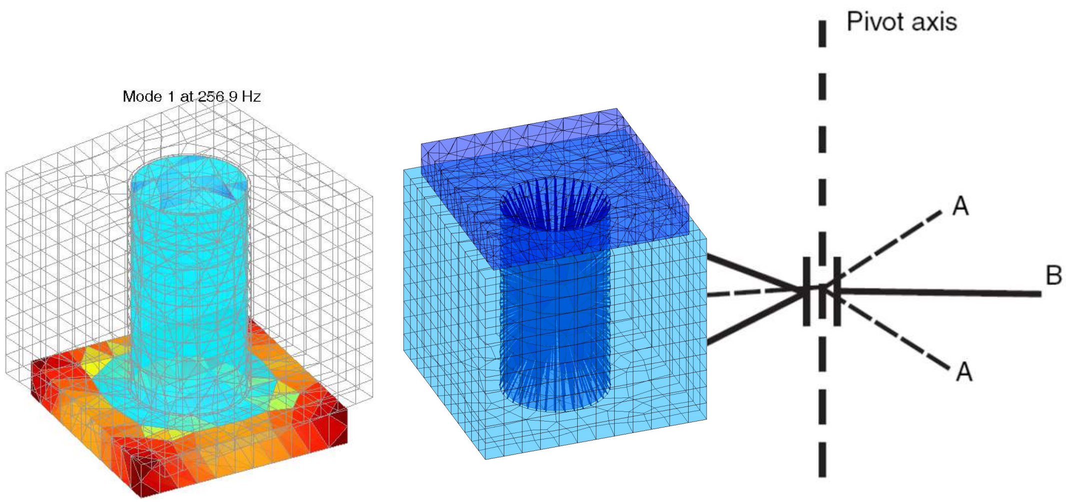
Master point : mass & stiffness error





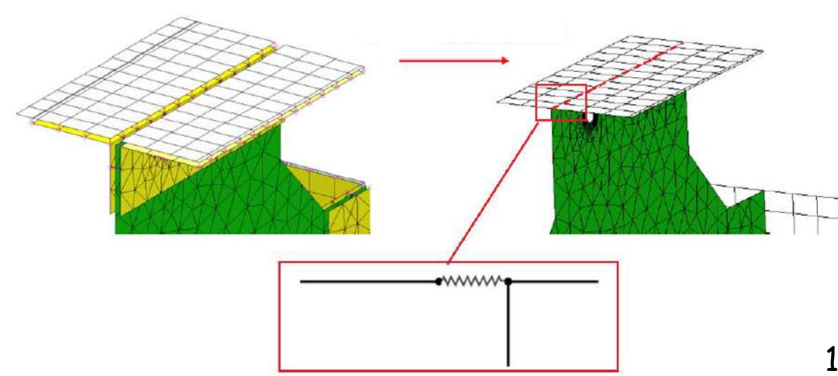


Kinematic junctions (pivots, …) often difficult with 2D



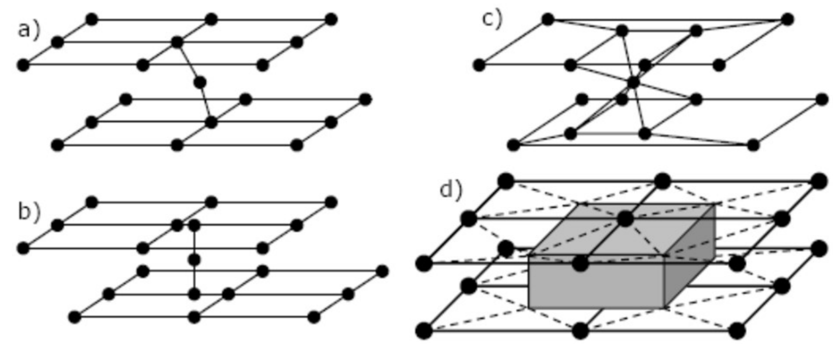
Contact : pivot mode at non zero frequency

Detail simplification (equivalent spring) may require complex numeric/test identification

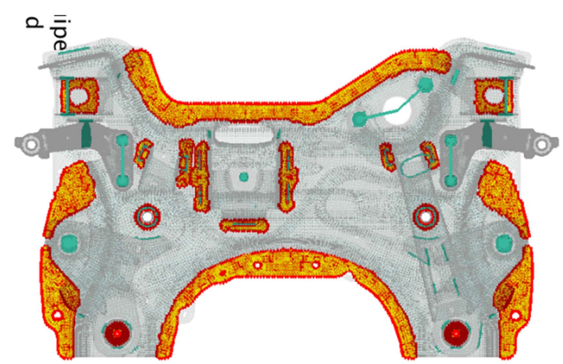


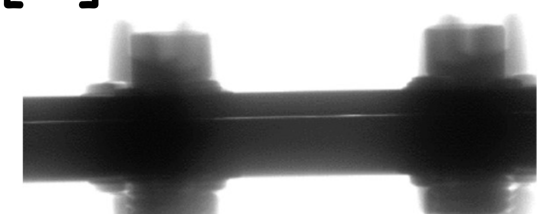
Junction problems : weld spots

- Weld spots [1]



- Contact around WS [2]



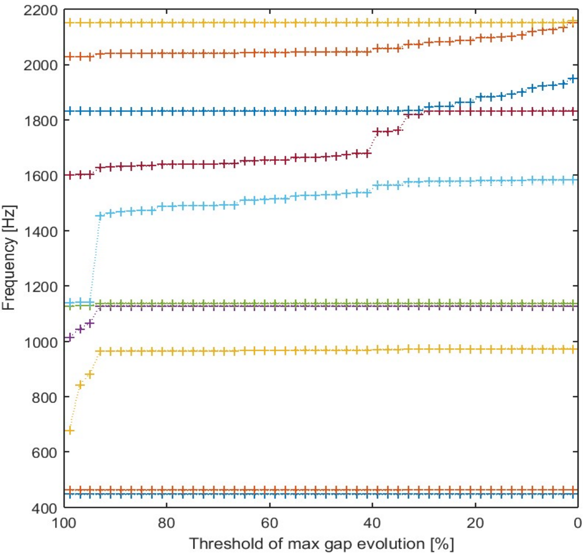


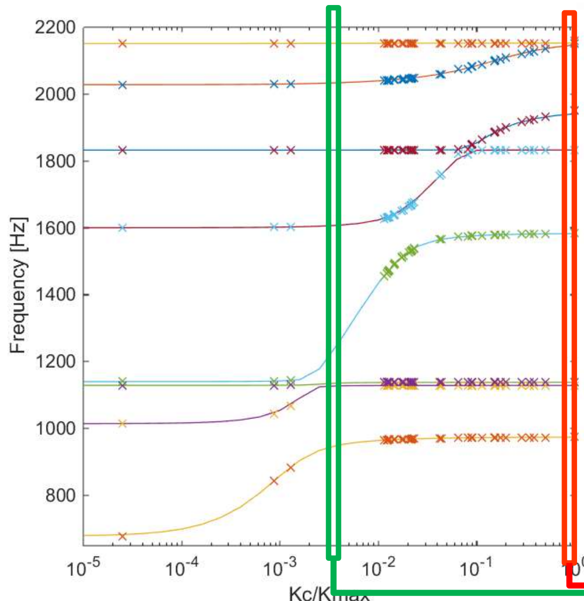
Tomography, M. Topenot, FEMTo, 2020

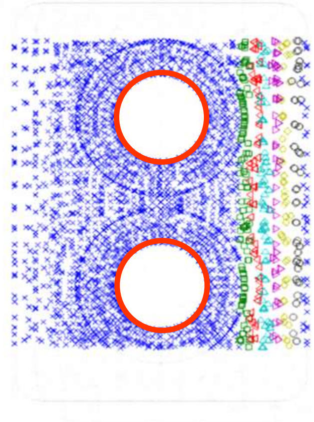
[1] Lardeur & All .: Spot weld modelling techniques and performances of finite element models for the vibrational behavior of automotive structures, ISMA 2000.
[2] G. Vermot Des Roches, E. Balmes, et S. Nacivet, « Error localization and updating of junction properties for an engine cradle model », in ISMA, 2016

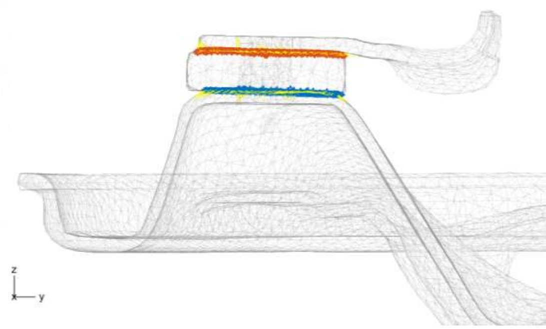
Junction : equivalent contact surface/stiffness

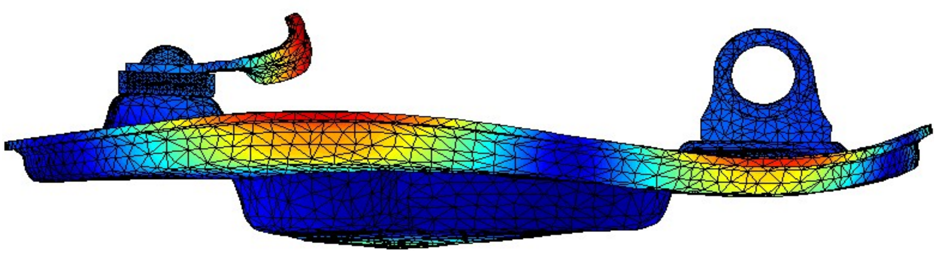
- Variable contact surface and stiffness
- Comparable impact frequencies and shapes

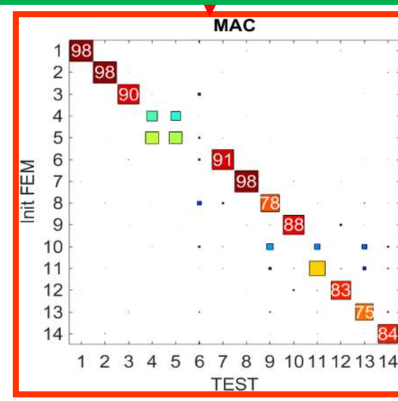


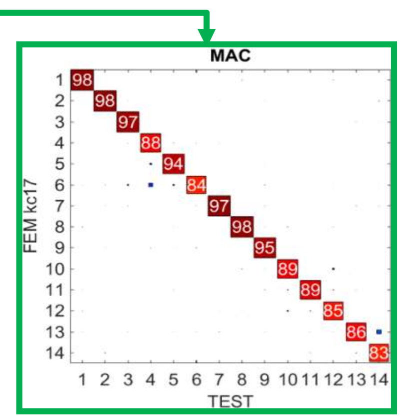






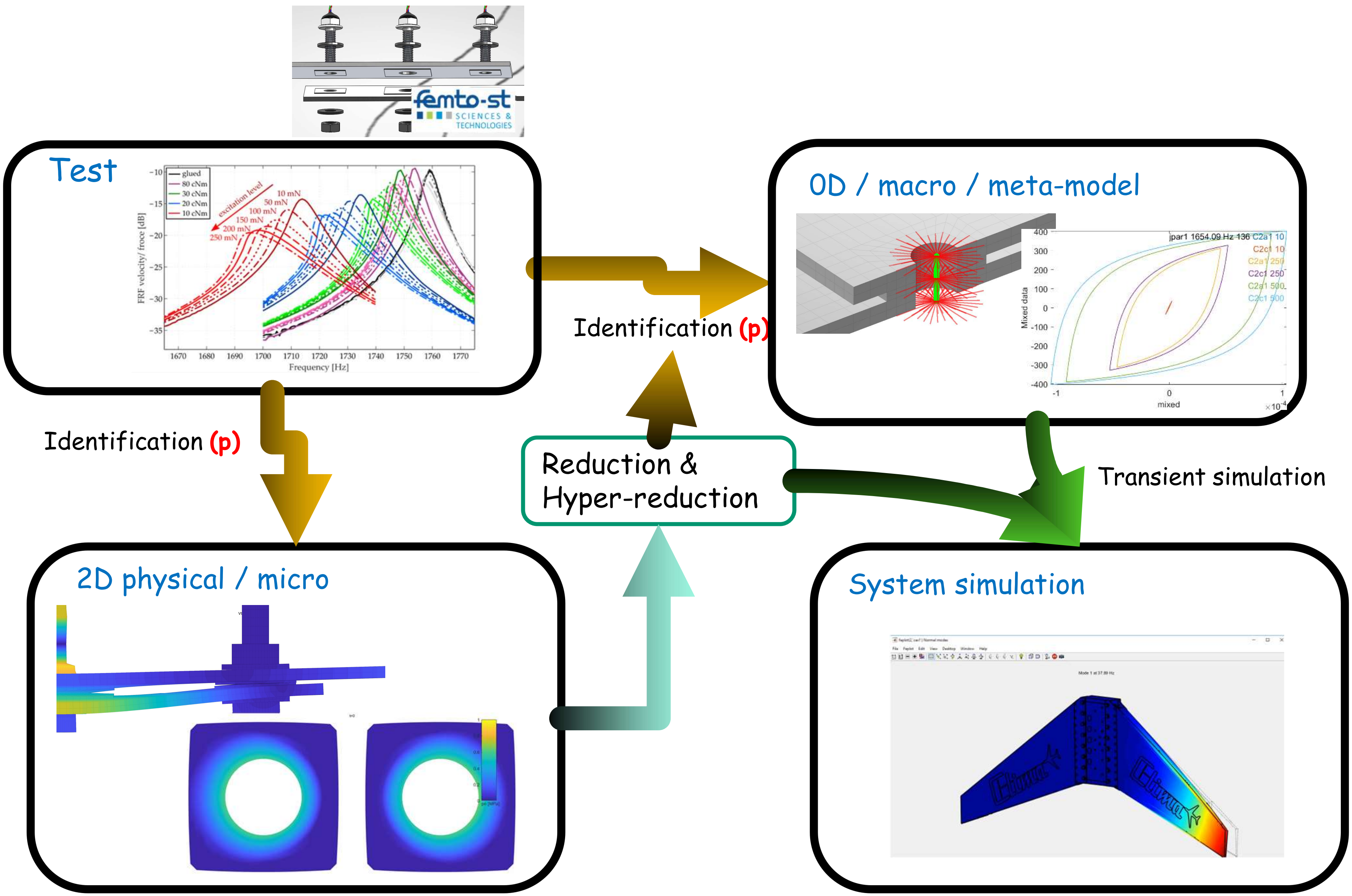






[1] G. Martin, E. Balmes, T. Chancelier, « Review of model updating processes used for brake components », in Eurobrake, 2015
[2] Y. Goth, H. Reynaud, « A bolt assembly parametric model », in ISMA, Leuven, 2016.

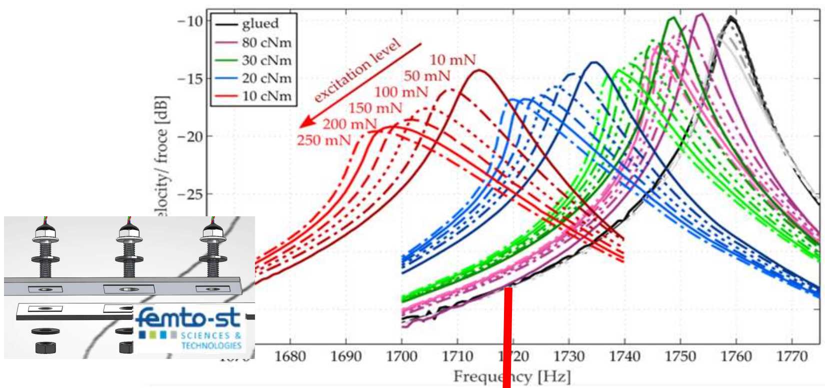
Contact/friction junction parameters

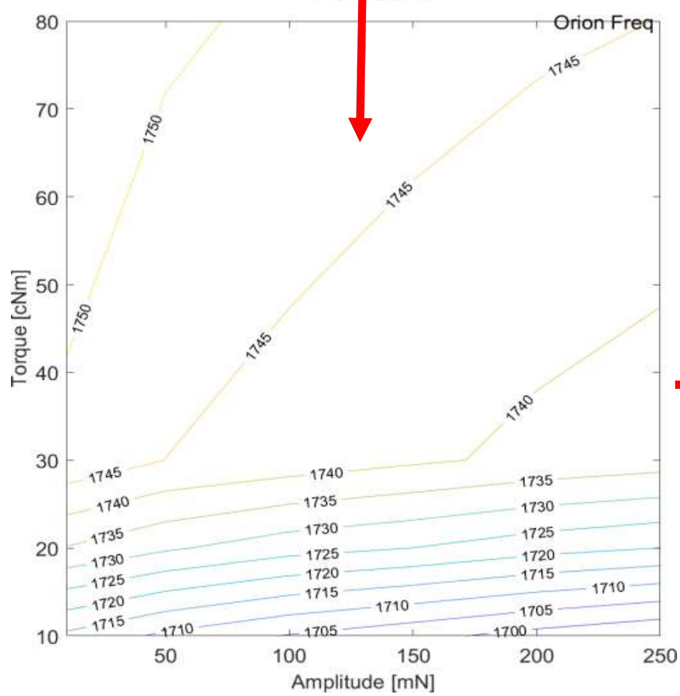


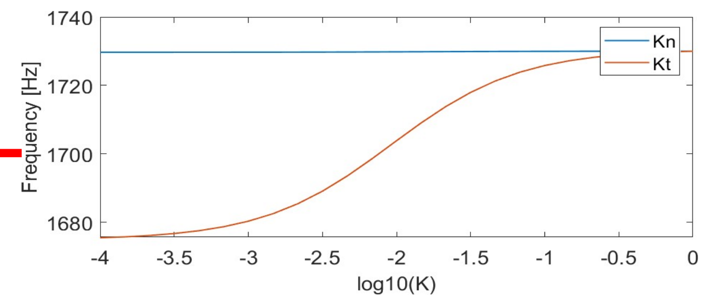
[1] FUI CLIMA (Conception de LIaisons Mécaniques Amortissantes)
[2] Thèse Marco Rosatello. Supméca 2019

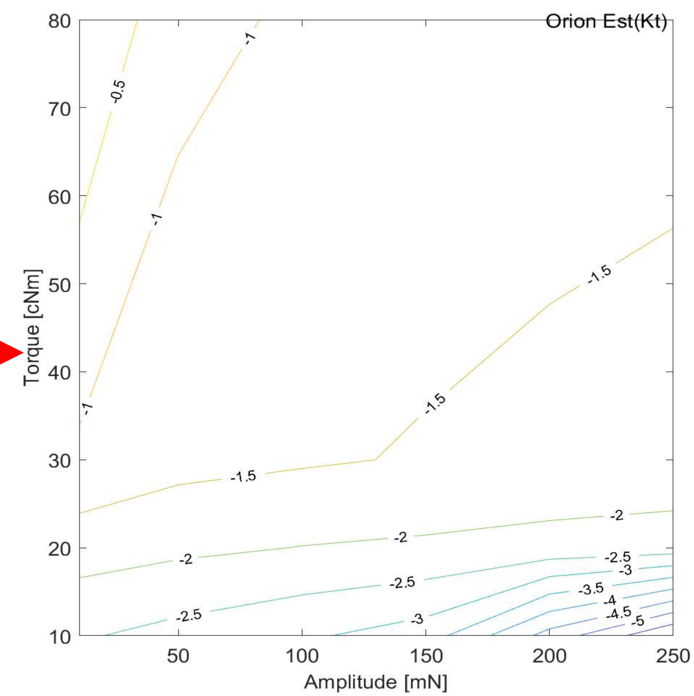
Equivalent stiffness : frequency/stiffness map

- Sensitivity to prestress/amplitude -> tangent stiffness map



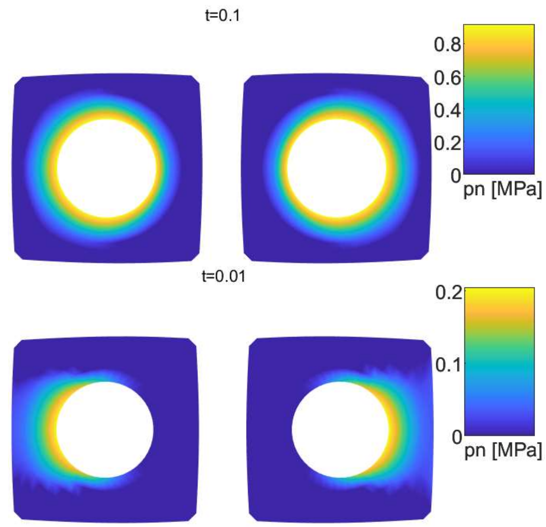


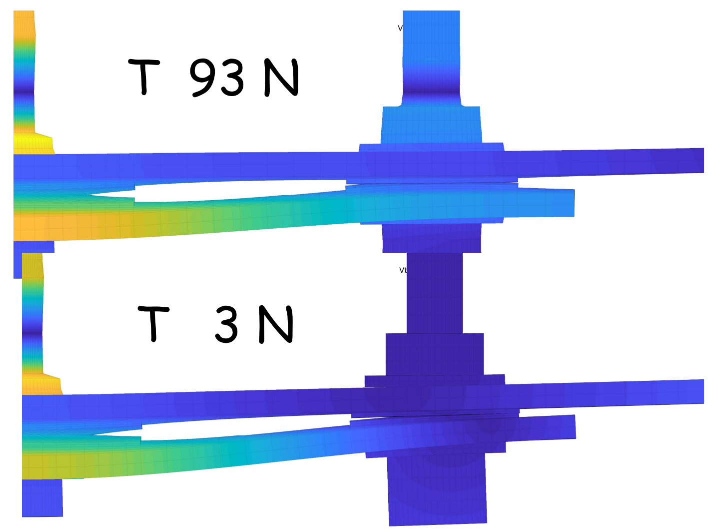




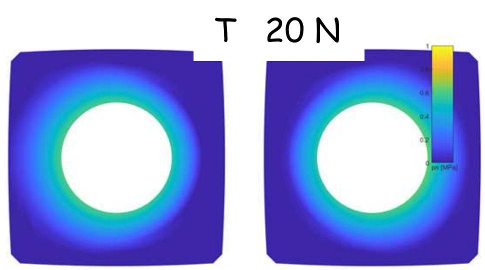
Numerical methologies useful/necessary to treat 2D

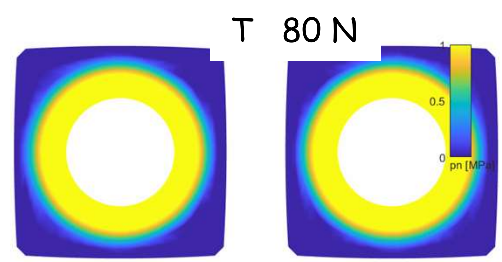
- StaticStatus
  iterate on nodes either bilateral or no contact



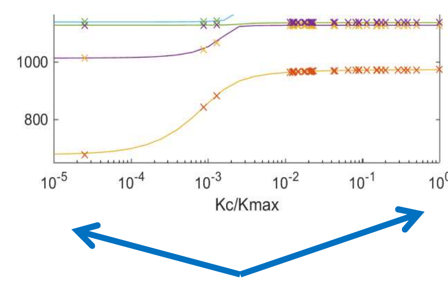


- StaticModeTraj [1]
  series of statics with $[M]\{\phi_j\}$ load





- Multi-model reduction [2]
  Ritz analysis on a few learning points

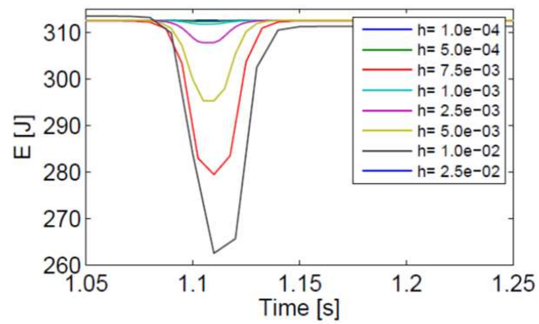


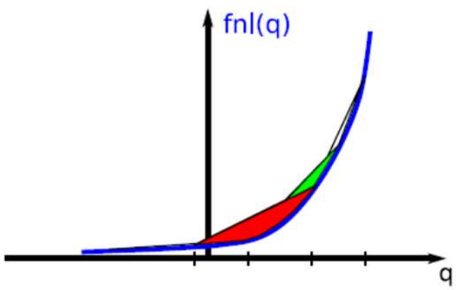
[1] H. Festjens, G. Chevallier, et J. Dion, « A numerical tool for the design of assembled structures under dynamic loads », IJMS, vol. 75, 2013
[2] Hammami, Balmes, Guskov, « Numerical design and test on an assembled structure of a bolted joint with viscoelastic damping », MSSP 2015.

Contact & need for equivalent laws

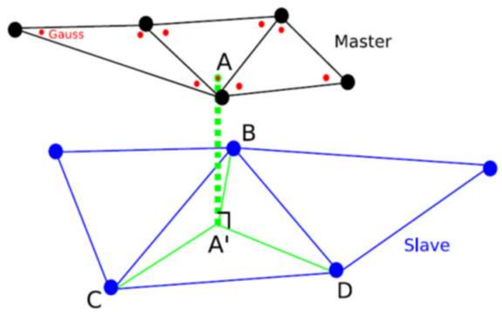
Physical contact laws are sensitive to accuracy on

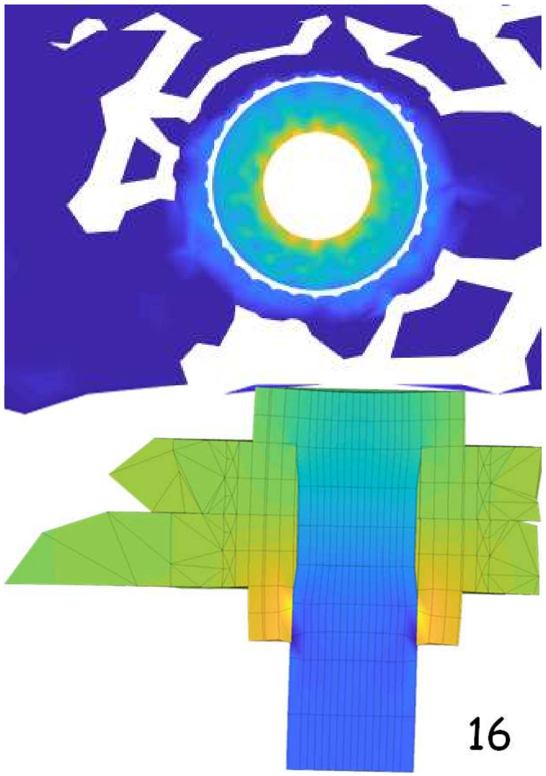
- Time events





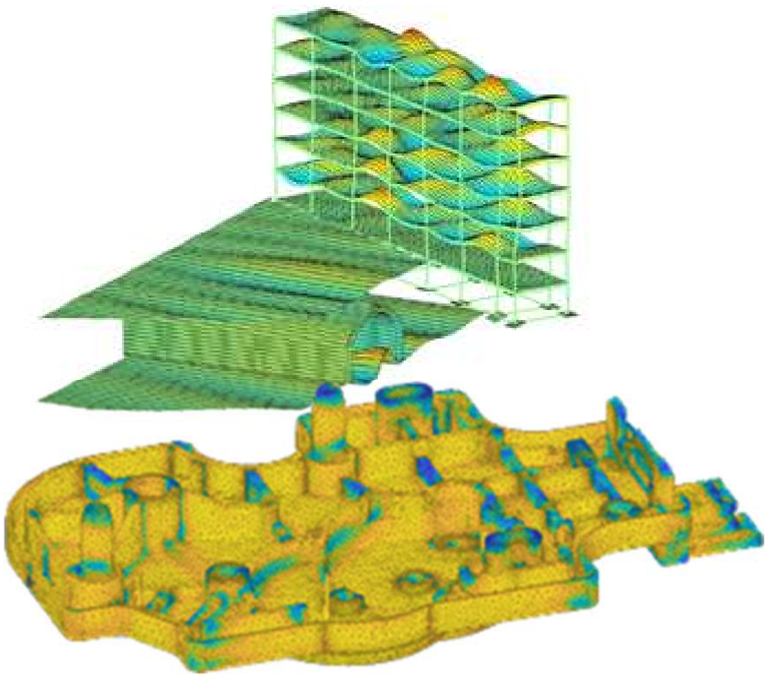
- Spatial events

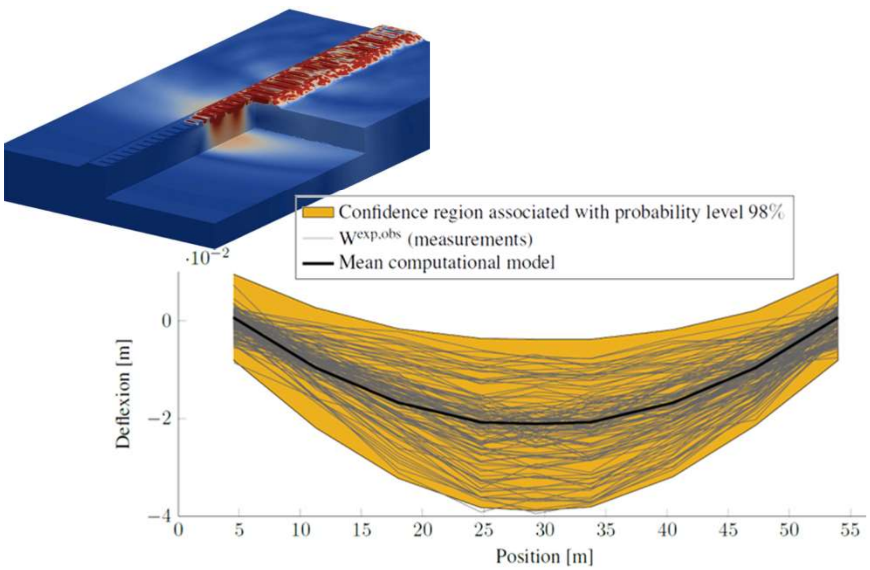




Equivalent 2D law needed to approximate both

Unknown/random/variable characteristics





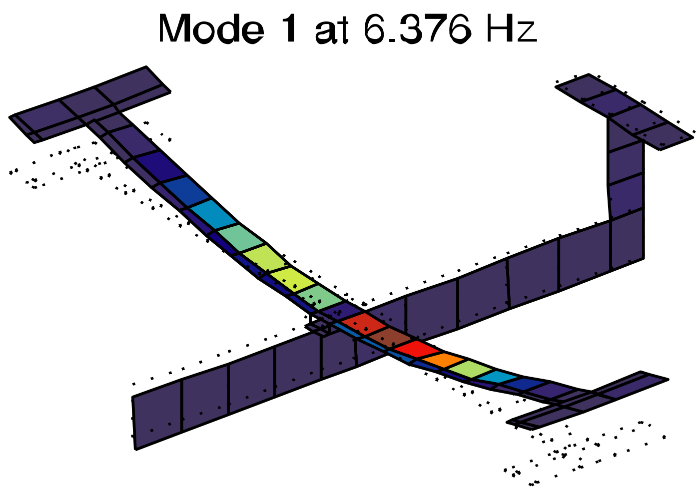
- Properties : soils, concrete, composite microstructure, ballast, …
- Loads (wind, waves, boiling water, …)

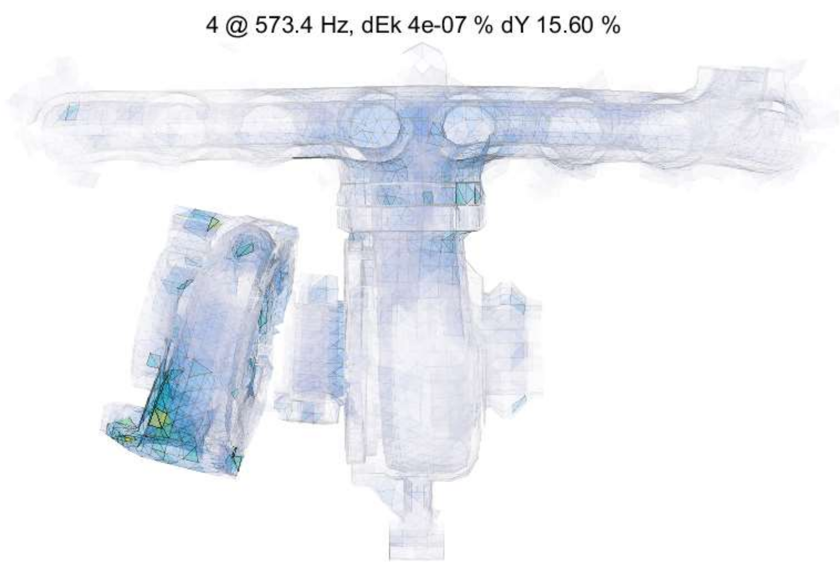
Needs

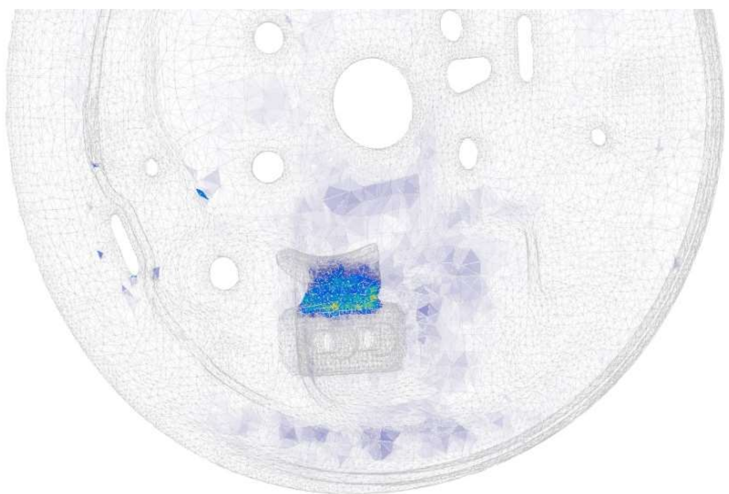
- Better knowledge (reduce uncertainties)
- A statistical description of uncertain fields
  - parametric (polynomial chaos, …)
  - Modal (non-parametric, see Soize & al.)
- A propagation method : from random model to random response

Measurement error -> localization

In MDRE (section 9.5, slides 8_correlation)
expansion the energy distribution of the displacement residual ($R_d\hat{}^T K^{(e)} R_d$) gives a localization







Summary : updating & modeling errors

Usual modeling errors (solution : detailed model/equivalent par.)

- Incorrect model (joints, geometry, …)
- Variability of physical parameters : geometry, properties
- Un-modeled physics (damping, contact, non-linearities material and geometric, …)
- Discretization / mesh convergence / FEM parameter
- User input errors

Legitimate updating parameters

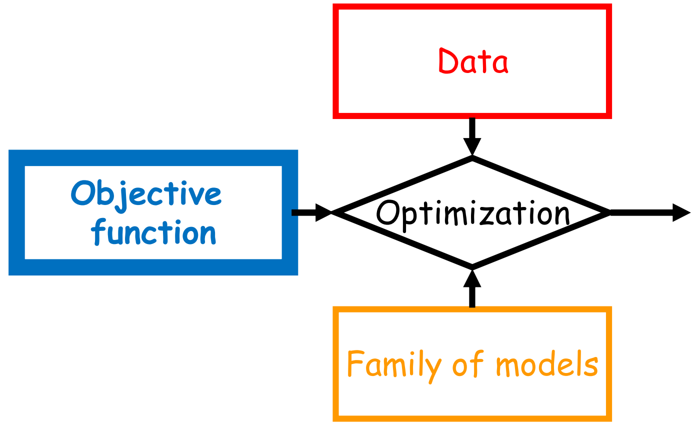
- Material parameters
- Equivalent macro-parameters : junction/contact stiffness
- Geometry

Next :

- Objectives
- Numerical tools for selection of parameters

Numerical methods for inverse problems (S11.5)

- Objective is often of the form $J = || R ||^2$
  example frequency sensitivity



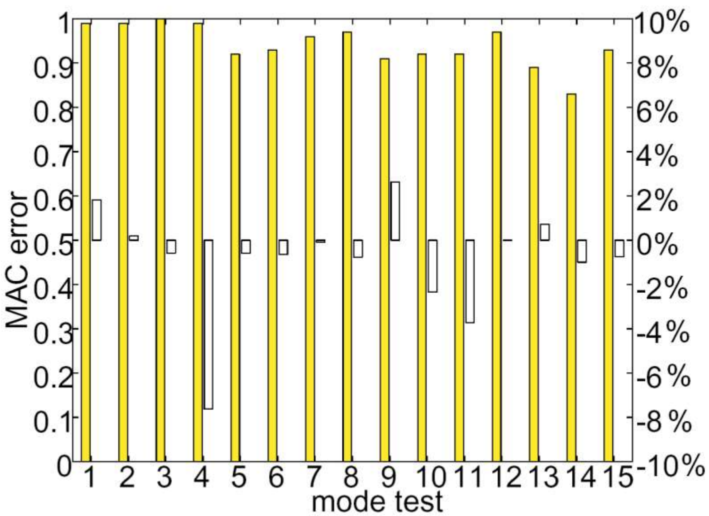
- Main effects
  - Parameter equivalence (poor conditioning)
  - Saturation (range where parameter is insensitive)
  - Parameter scaling
  - Parameter grouping (element divided in 2 $\Rightarrow$ sensitivity too)

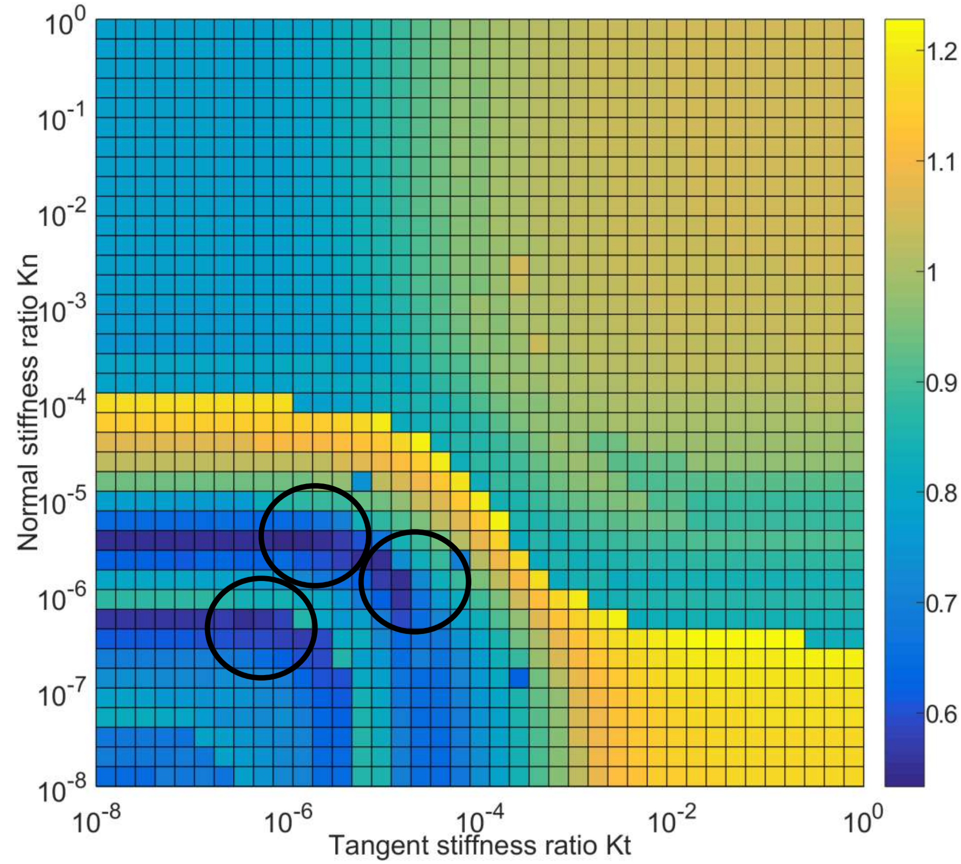
Freq-MAC objective

$$R_j(p) = \left\{ \begin{array}{c} \frac{f_{EF,i} - f_{Test,j}}{f_{Test,j}} \\ \beta(1 - MAC_{i,j}) \end{array} \right\}$$

$$J_{freq-MAC}(p) = \sqrt{\sum_{j=1}^{NM} \|R_j(p)\|^2}$$

Problems
- $J_{freq\text{-}MAC}$ irregular
- Jumps on mode pairing.
- Can be difficult to minimize

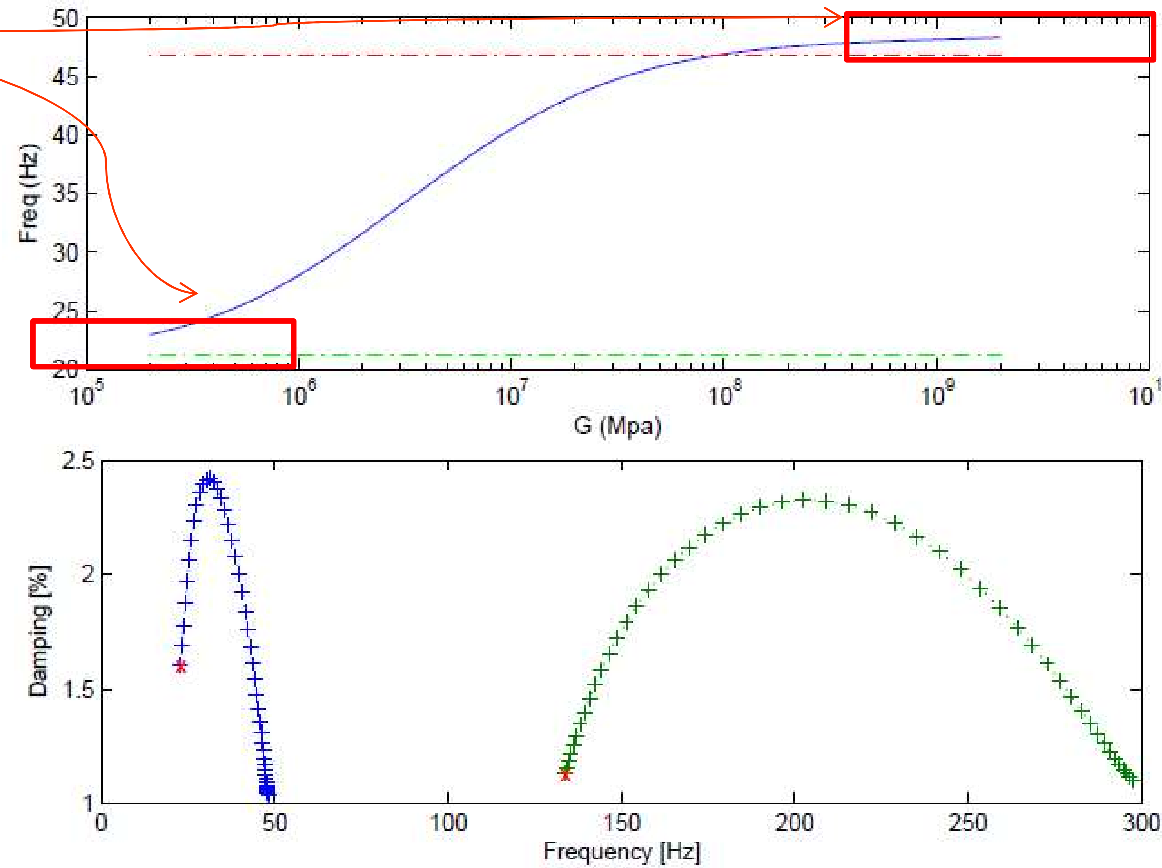




PhD. G. Martin, Méthode de corrélation calcul/essai pour l'analyse du crissement

Large scale and sensitivity saturation

- Structural parameters typically have saturation ranges for both low and high values
- Sensitive range needs to be determined first



Non-linear least squares

$$J(p) = \|R\|_2^2 = \text{Trace}\left(R^T R\right) = \sum_{i,j} \bar{R}_{ij} R_{ij}$$

- First derivative

$$\frac{\partial J(p)}{\partial p} = 2\text{Trace}\left(\frac{\partial R^T}{\partial p} R\right)$$

- Second derivative

$$\frac{\partial^2 J(p)}{\partial p^2} = 2\text{Trace}\left(\frac{\partial R^T}{\partial p}\frac{\partial R}{\partial p} + R^T \frac{\partial^2 R}{\partial p^2}\right)$$

Often neglected

- Newton method $p^{n+1} = p^n + \delta p^{n+1}$ with

$$\left[\frac{\partial^2 J(p)}{\partial p^2}\right]\left\{\delta p^{n+1}\right\} + \left\{\frac{\partial J(p)}{\partial p}\right\} = \{0\}$$

- Convergence

$$\lambda_{\max}\left(\left[\frac{\mathrm{d}^2 J}{\mathrm{d}p^2}(p)\right]\right) < 1$$

Sensitivity method

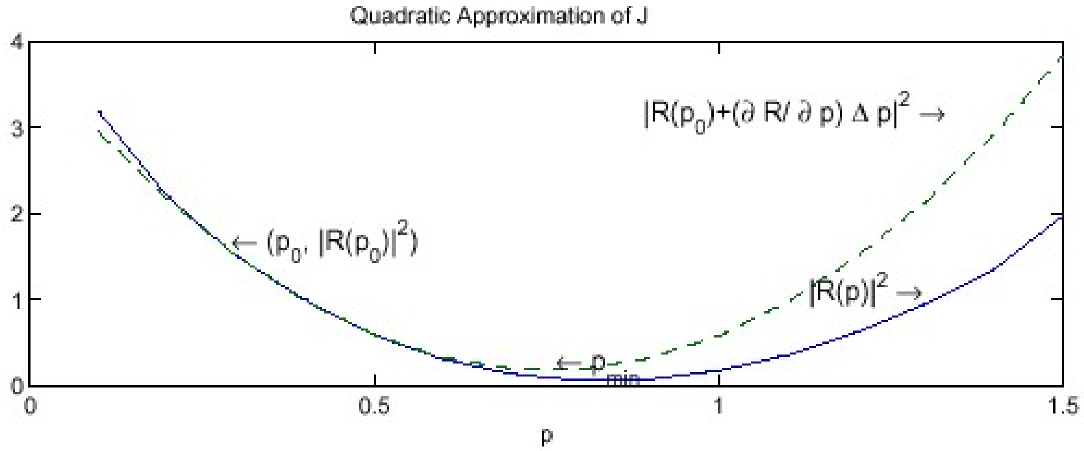
- Approximation of second order derivative ⇒

$$\text{Trace}\left(\left\{\frac{\partial R}{\partial p}\right\}^T \quad \left(\frac{\partial R}{\partial p}\left\{\delta p^{n+1}\right\} - R(p^n)\right)\right) = 0$$

- Equivalent to (with appropriate norm)

$$\min_{\{\delta p^{n+1}\}} \left\| \left\{\frac{\partial R}{\partial p}\right\}\left\{\delta p^{n+1}\right\} - \left\{R(p^n)\right\} \right\|$$

- Standard least-squares form



Least squares conditioning

- One solves LS $$\min_{\{x\}} \|[A]\ \{x\} - [b]\|_2^2$$
- But errors $$([A] + [\delta A])\ (\{x\} + \{\delta x\}) \ = \ (\{b\} + \{\delta b\})$$

- Problem is well conditioned if :

$$\frac{\|\delta A\|}{\|A\|} \ll 1, \qquad \frac{\|\delta b\|}{\|b\|} \ll 1 \qquad \Longrightarrow \qquad \frac{\|\delta x\|}{\|x\|} \ll 1$$

- One can prove that (k condition number)

$$\frac{\|\delta x\|}{\|x\|} \ \leq \ \kappa(A) \left(\frac{|||\delta A|||}{|||A|||} + \frac{\|\delta b\|}{\|b\|} \right) \qquad \kappa(A) \ = \ |||A|||\ |||A^{-1}|||$$

Least squares and SVD

- SVD of A is of the form $$[A] = \sum_{j=1}^{\min(n,m)} \sigma_j \{U_j\} \{V_j\}^T$$
- Least squares solution given by

$$\{x\} = \sum_{j=1}^{\min(n,m)} \sigma_j^{-1} \{V_j\} \{U_j\}^T [b] = [V] \left[{}^{\backslash}\sigma_j^{-1}{}_{\backslash} \right] [U] [b]$$

- This is a Moore-Penrose pseudo-inverse

$$\begin{aligned}
\left[A^+\right] \; [A] \; \left[A^+\right] &= \left[A^+\right] \\
[A] \; \left[A^+\right] \; [A] &= [A] \\
\left([A] \; \left[A^+\right]\right)^T &= \left([A] \; \left[A^+\right]\right) \\
\left(\left[A^+\right] \; [A]\right)^T &= \left(\left[A^+\right] \; [A]\right)
\end{aligned}$$

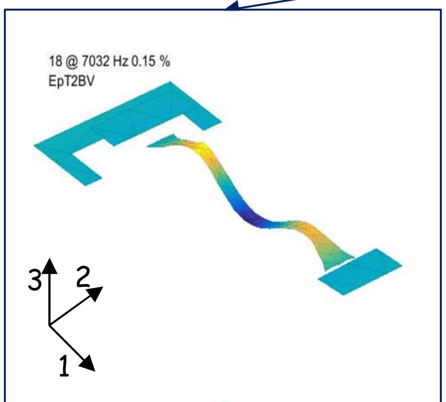
Parameter equivalence / conditionning

2 samples V/H

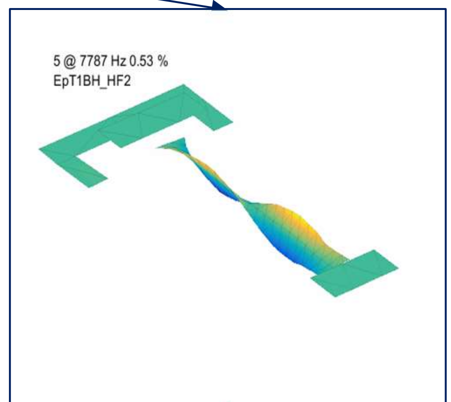
Tests

Observable modes

Vertical bending

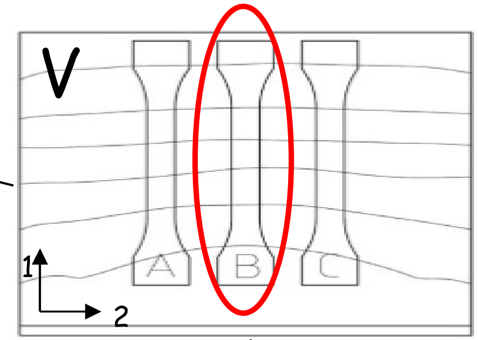


Torsions

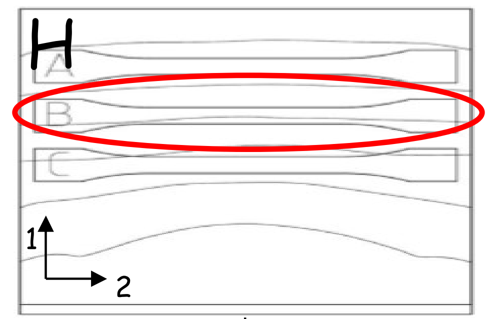


Identification

$$C^{-1} = S = \begin{pmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{pmatrix}$$



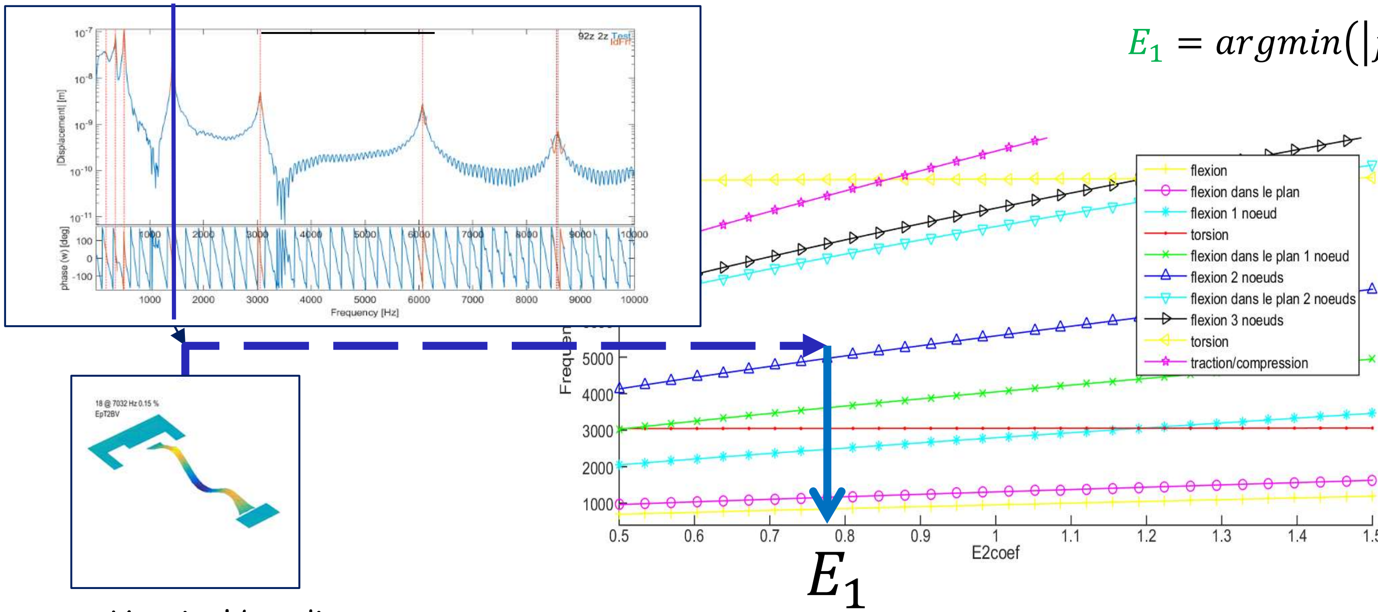
Identification of E_1 , G_{31} et G_{12}



Identification of E_2 et G_{23} $(+G_{12})$

Parameter equivalence : material example

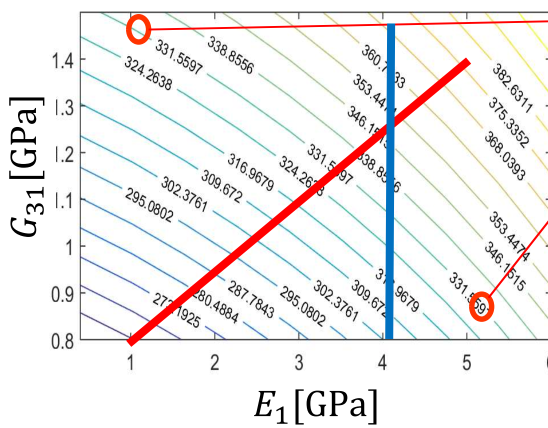
$$E_1 = argmin(|f_{flexion}(E_1, G_{31}) - f_{flexi\ \ ,obj}|)$$



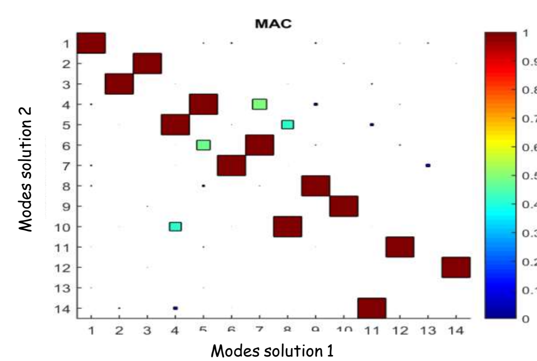
Vertical bending

Assumption must be made to improve conditioning

- G_{31}/E_1 constant ?
- E_1 traction ?

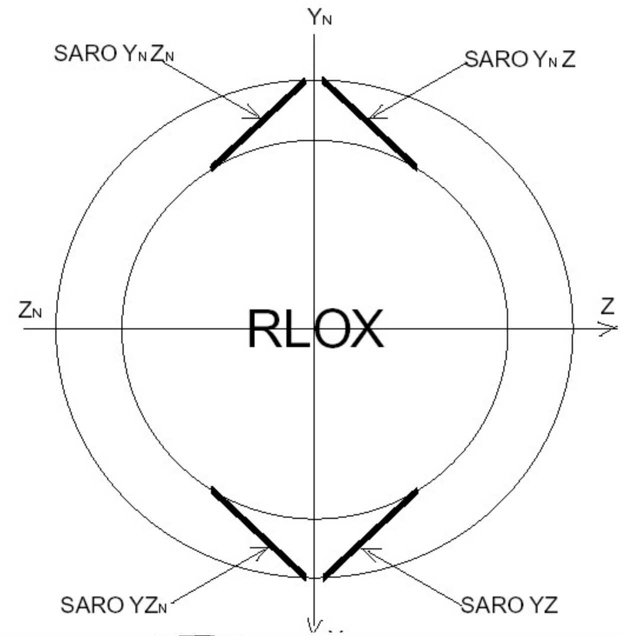


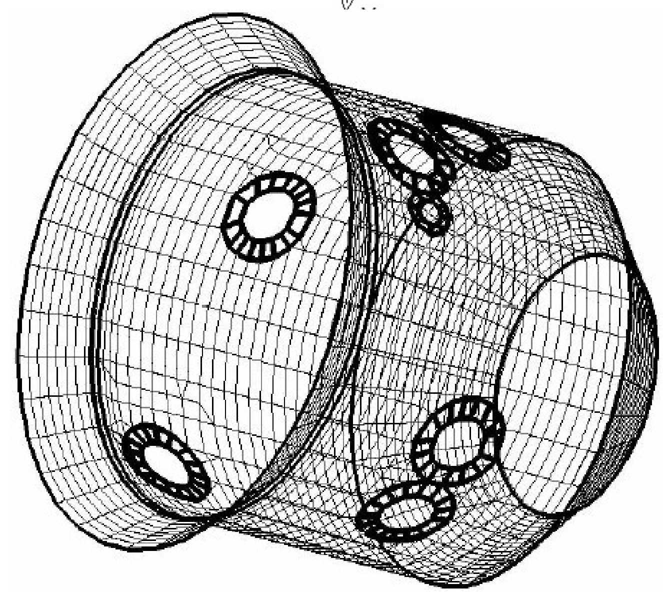
Solution is not unique
Mode-shape very similar



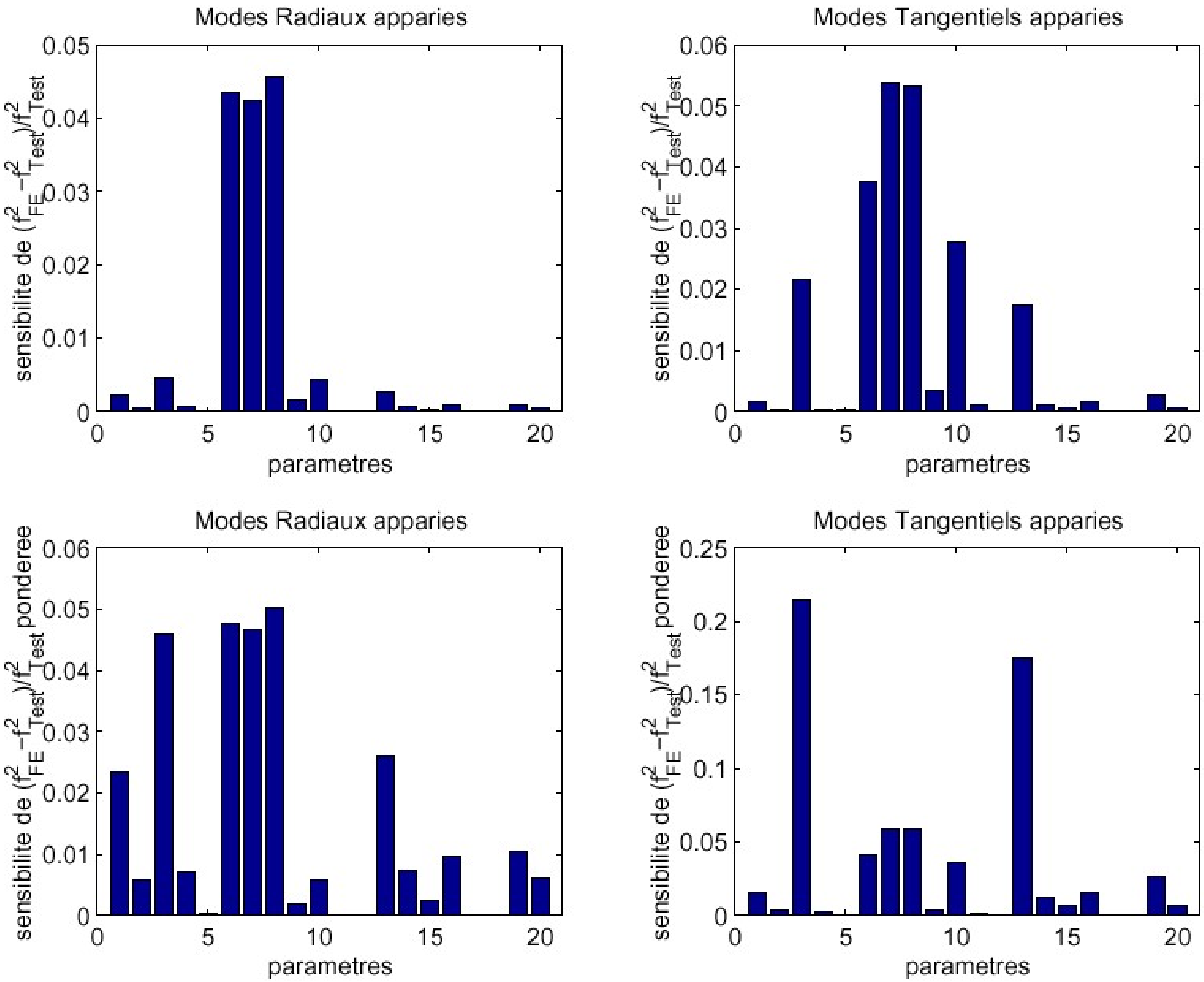
Parameter selection and range setting

paramètre	variation relative autorisée
Raideur SARO YZ (situé dans la partie $Y > 0$ et $Z > 0$ du modèle)	$0.5 - 2$
Raideur SARO YNZ (situé dans la partie $Y < 0$ et $Z > 0$ du modèle)	$0.5 - 2$
Raideur SARO YNZN	$0.5 - 2$
Raideur SARO YZN	$0.5 - 2$
Raideur *ITS struts*	$0.5 - 2$
Raideur *ITS ring*	$0.5 - 2$
Raideur des couronnes d'éléments autour des trous SYLDA5	$0.2 - 5$
Raideur Vérin maquette moteur situé dans la partie $Z > 0$	$0.5 - 2$
Raideur Vérin maquette moteur situé dans la partie $Z < 0$	$0.5 - 2$
Position de la masse ponctuelle de la maquette moteur 170Kg (3 paramètres)	$-0.1\text{m} < \text{dx} < 0.1\text{m}$ $-0.1\text{m} < \text{dy} < 0.1\text{m}$ $-0.1\text{m} < \text{dz} < 0.1\text{m}$
Position de la masse ponctuelle de la maquette moteur 56.8Kg (3 paramètres)	$-0.1\text{m} < \text{dx} < 0.1\text{m}$ $-0.1\text{m} < \text{dy} < 0.1\text{m}$ $-0.1\text{m} < \text{dz} < 0.1\text{m}$





Sensitivity : frequencies



Stiffeners (13)

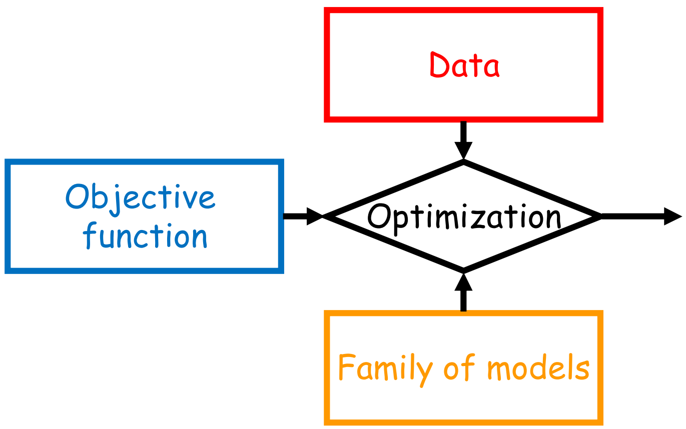
Segments (6-8, 10)

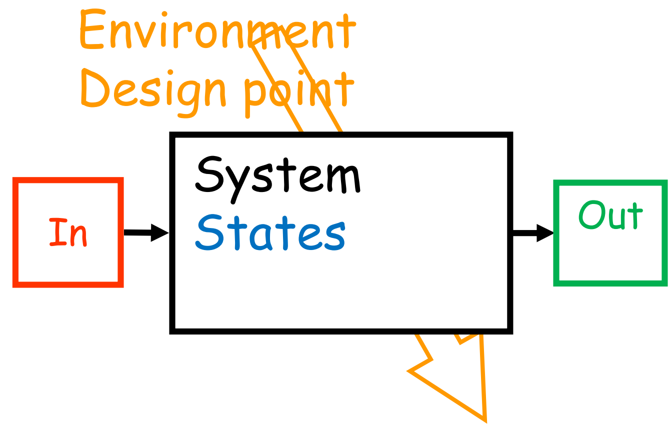
Caliper diagonal(3)

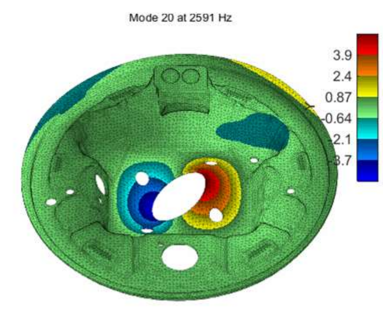
Same conclusion with MAC

Theory : shape sensitivity, relation with strain/kinetic energy

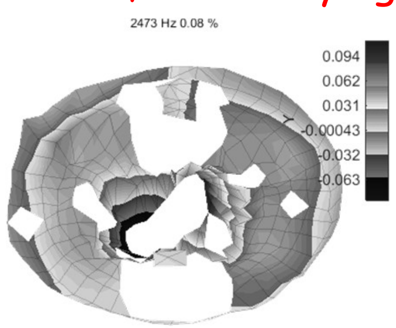
Parametric inverse problems



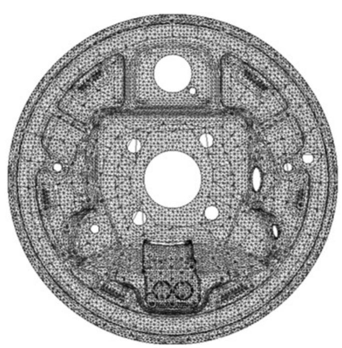




Identification error
- Noisy measurements
- Identification bias
- NL, time varying, …

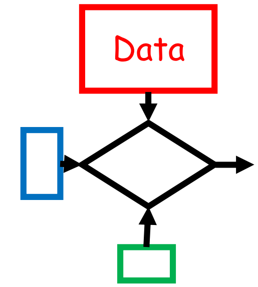


Topology errors
- sensor/act position
- matching



FEM error
- Geometry
- Material parameters
- Multi-scale problems & equivalent parameters
- Junction representation
- Design change & modal property tracking

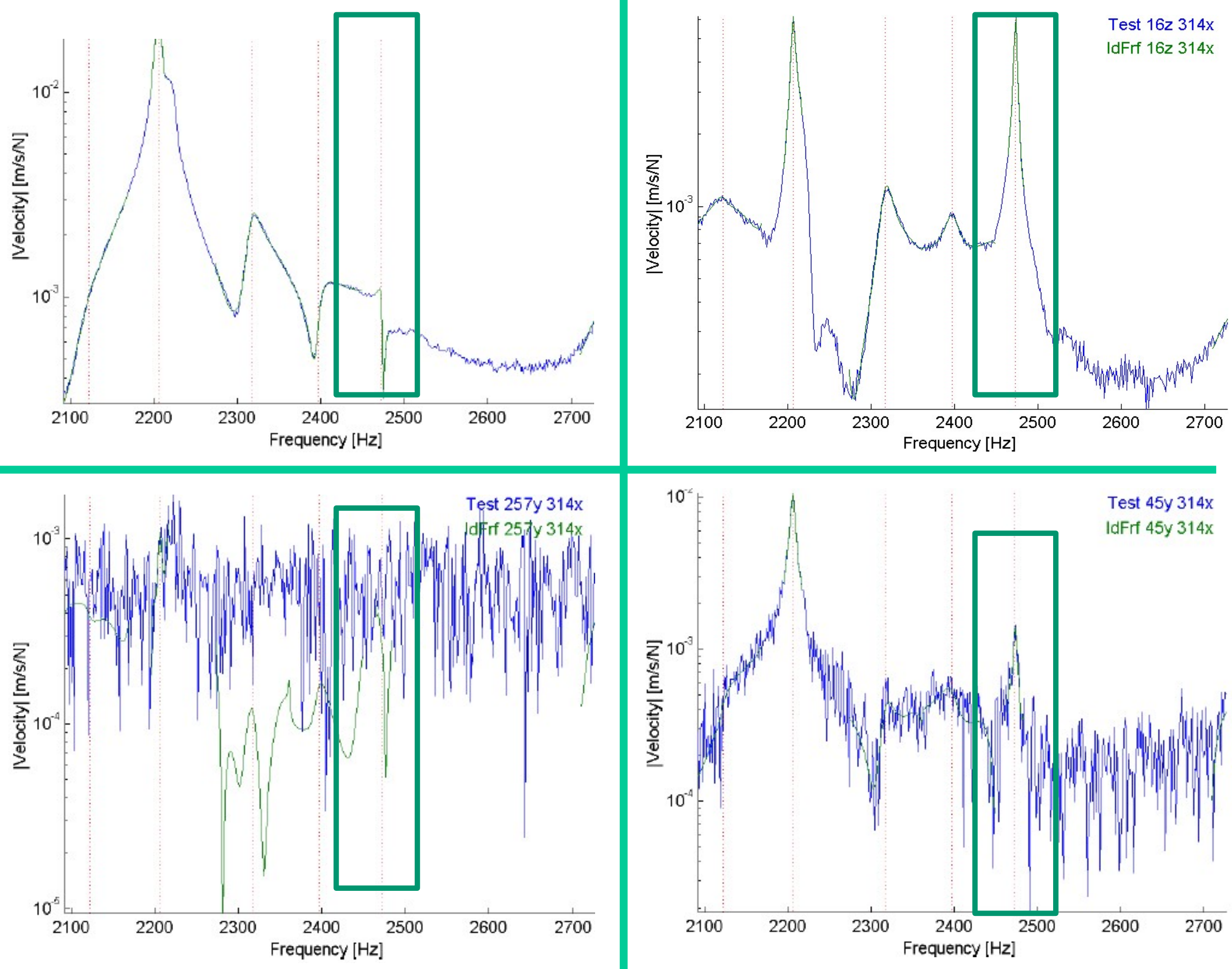
Test/identification error



Contribution -- | Contribution ++

Error --

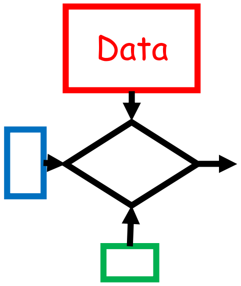
Error ++



For each sensor, each mode may have strong error/noise & low contribution

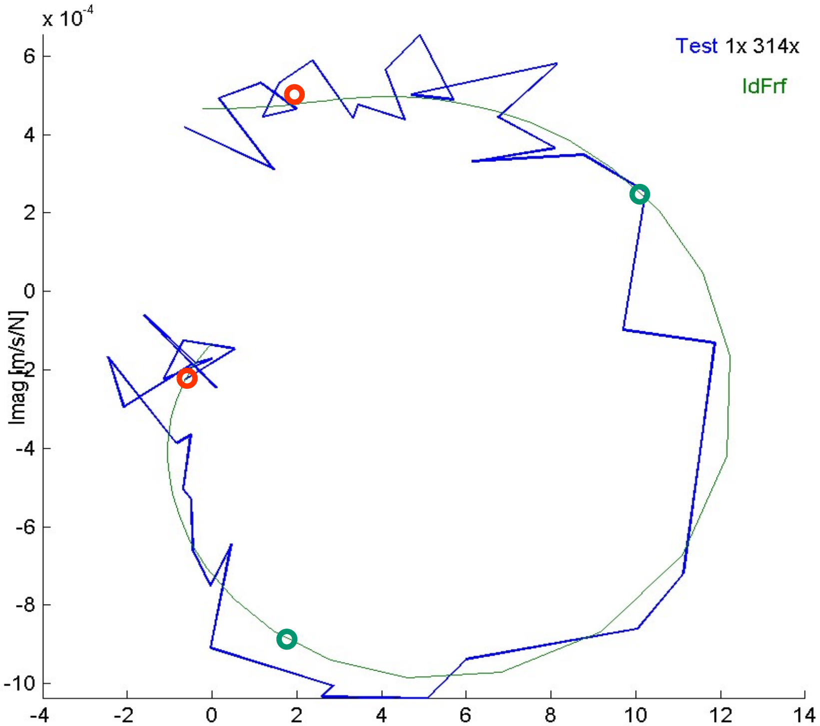
Need for a per mode/sensor definition of test error

Quality : Error Criterion



Is the model well identified?

- Superpose measured and identified FRF for each sensor, around each mode
- Compute error on Nyquist

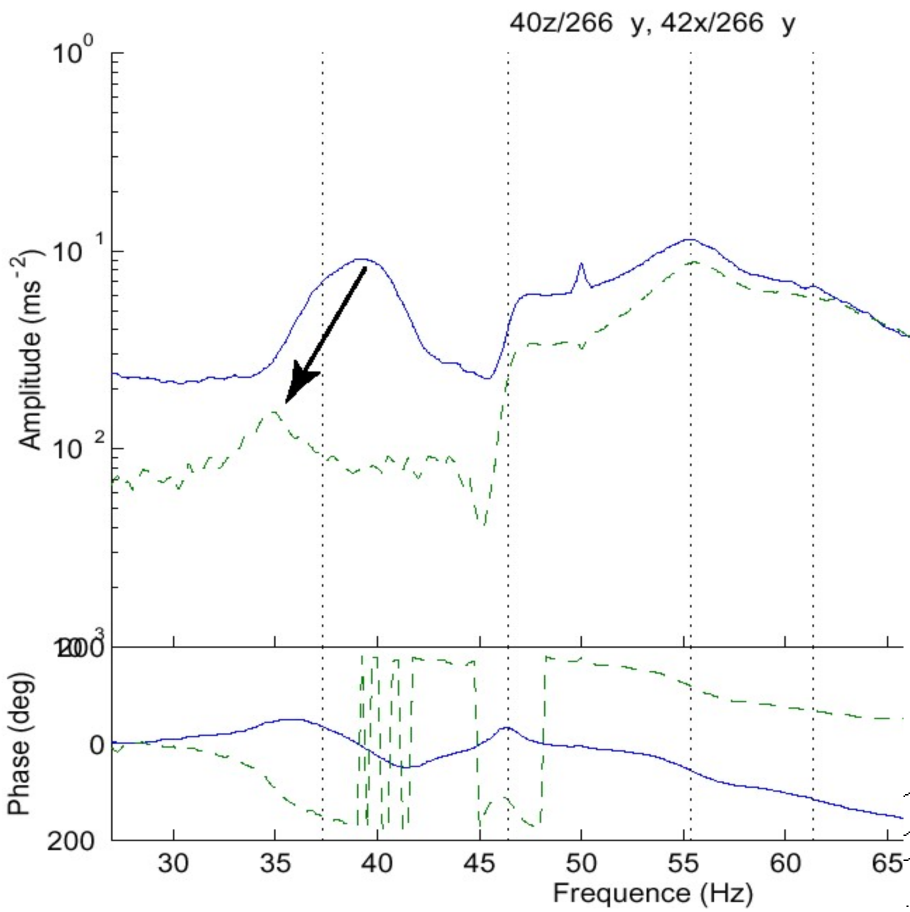


$$e_{j,c} = \frac{\int_{\omega_j(1-\zeta_j)}^{\omega_j(1+\zeta_j)} |H_{Test,c}(s) - Hid, c(s)|^2}{\int_{\omega_j(1-\zeta_j)}^{\omega_j(1+\zeta_j)} |H_{id,c}(s)|^2}$$

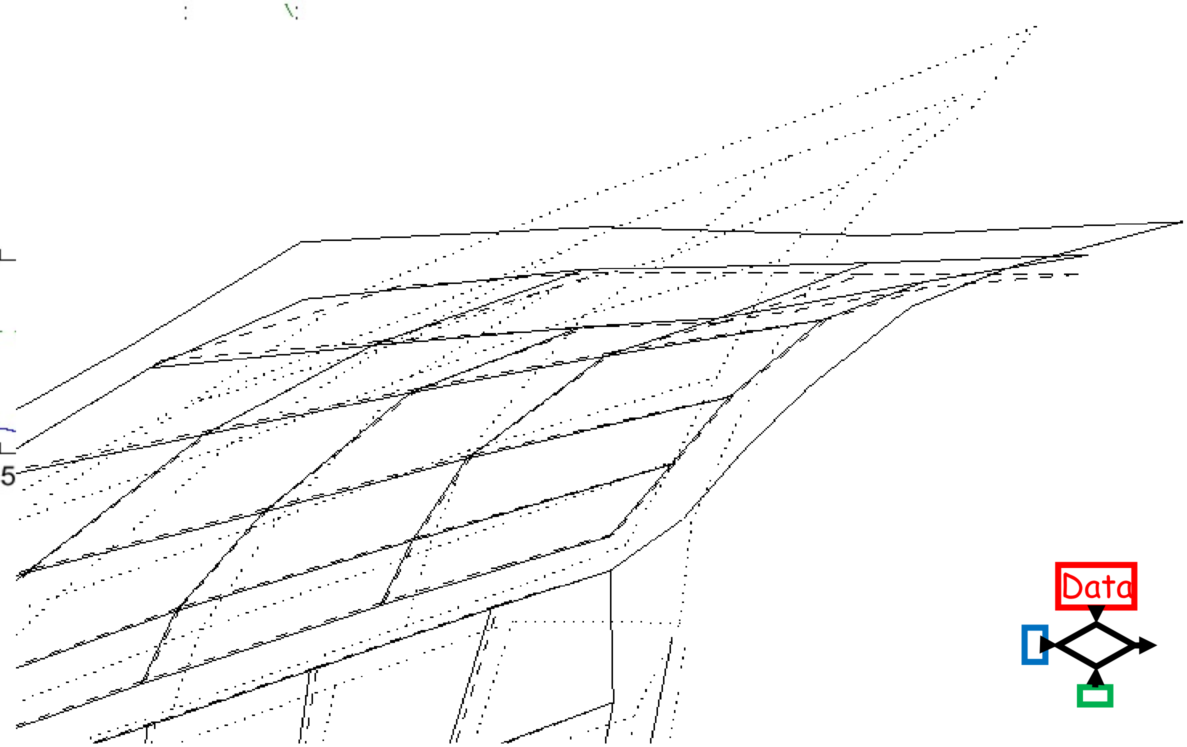
"Around each mode" :

- Half power : +/- $\zeta_j\omega_j$
- Visible peak : +/- $5\zeta_j\omega_j$

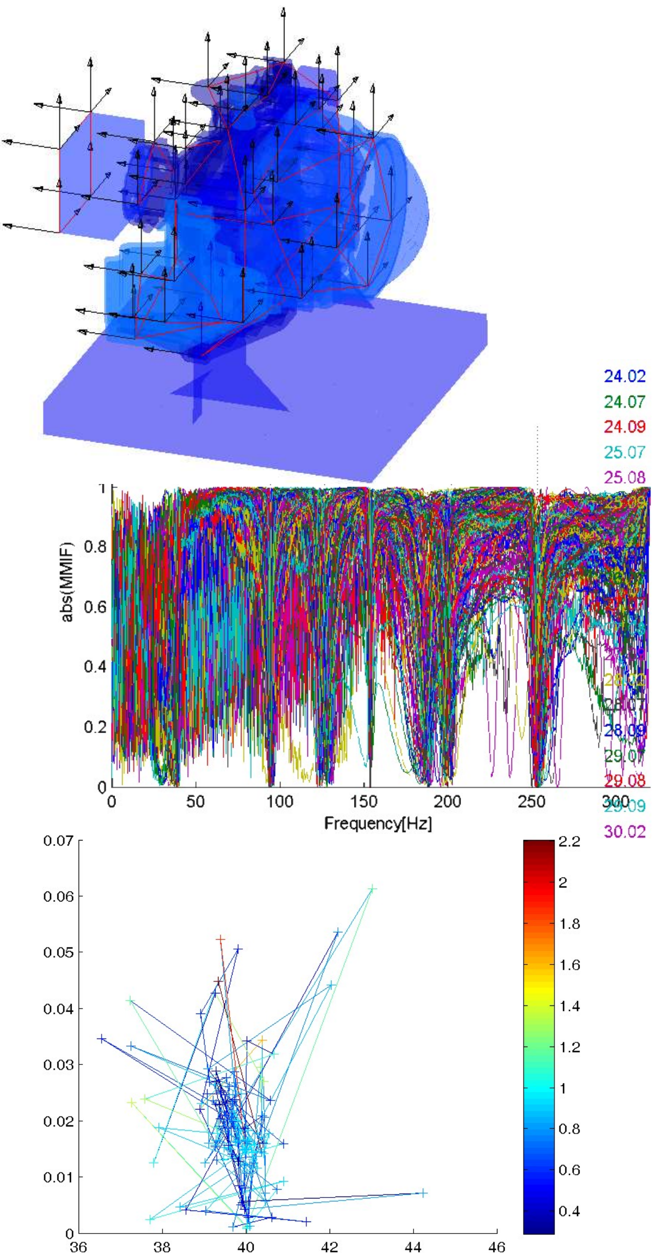
Invariance : test with sensor batches



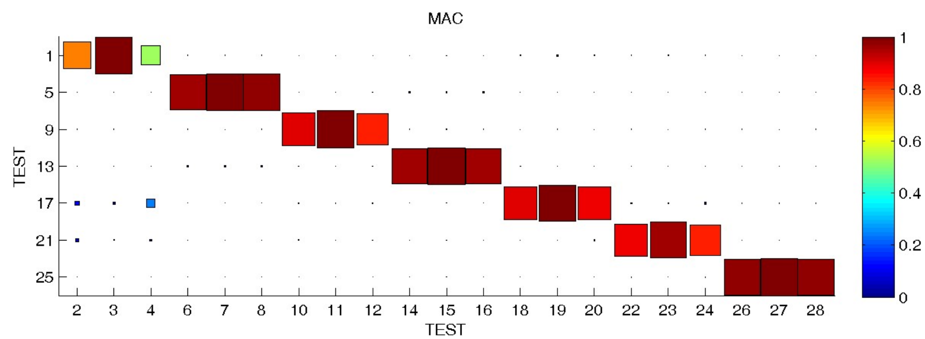
- With test batches, the system may not be invariant
- Reciprocity may be a problem



Non-linearity & invariance

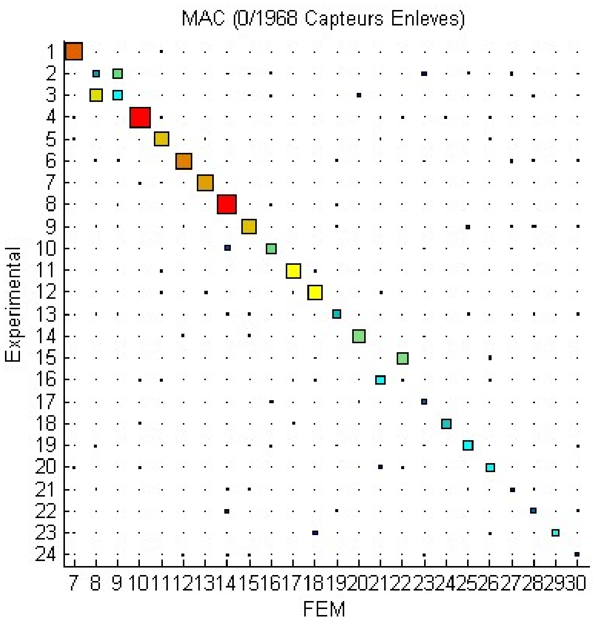


- Non linear system : resonance dependent on input point
- MMIF or identification per impact location shows significant dispersion
- Multiple identification results are not perfectly coherent

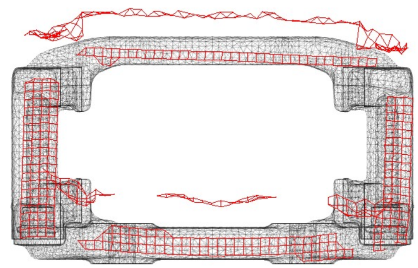


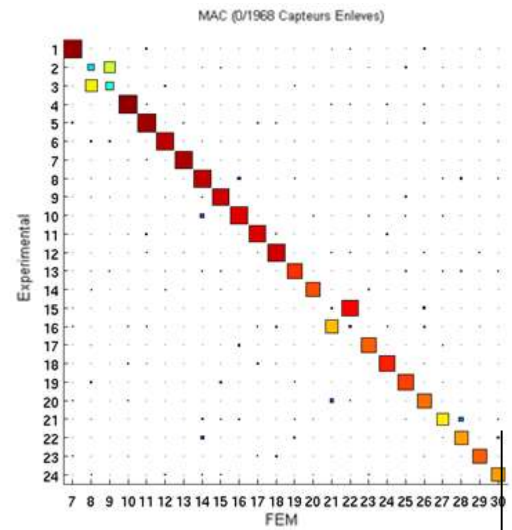
Data courtesy VALEO Lighting Systems

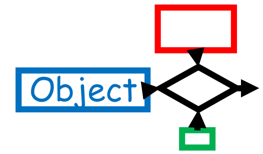
Topology error / measurement error



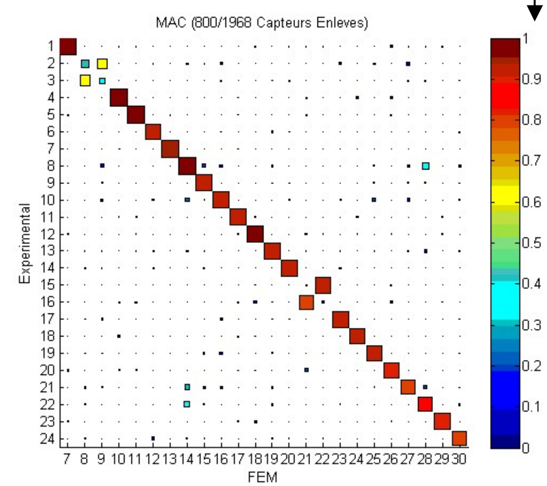
Correction of experimental positions





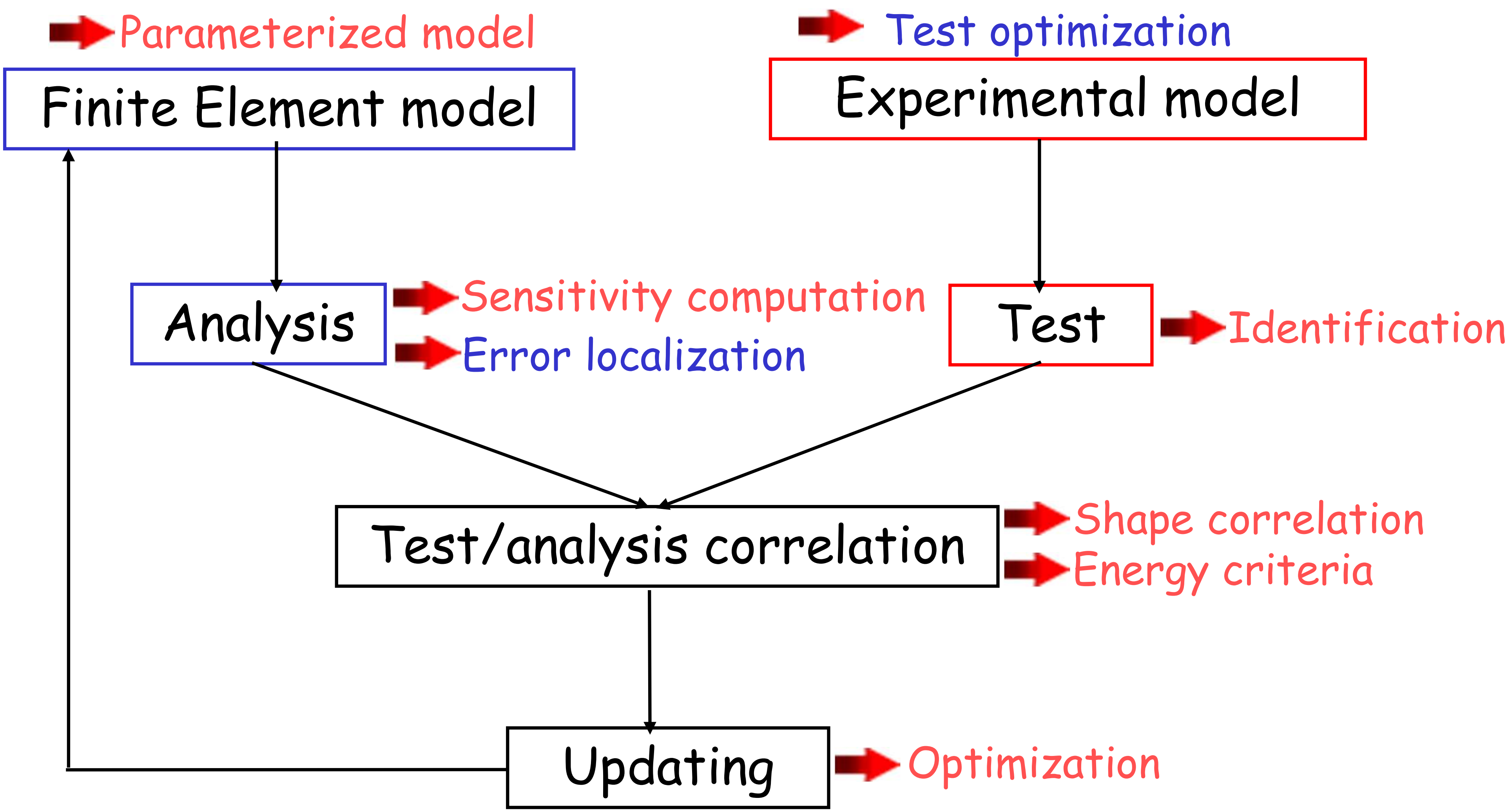


MAC Co suppression of bad sensors



CHASSIS BRAKES INTERNATIONAL

Updating


Parameterized model
Finite Element model
Test optimization
Experimental model
Analysis
Sensitivity computation
Error localization
Test
Identification
Test/analysis correlation
Shape correlation
Energy criteria
Updating
Optimization