Méthodes et outils pour la surveillance vibratoire et l'identification des structures aéronautiques

J. MORLIER

INRIA IRISA-Rennes, Le 15 avril 2010

Le contexte toulousain

L'**Institut Clément Ader** regroupe des personnels appartenant à quatre grands établissements d'enseignement et de recherche de la région Midi-Pyrénées :

- l'Ecole des Mines d'Albi-Carmaux
- l'Institut National des Sciences Appliquées de Toulouse
- l'Institut Supérieur de l'Aéronautique et de l'Espace (ISAE)
- l'Université Paul Sabatier, Toulouse 3 (UPS)

Sommaire

- Quelques mots sur l'ISAE et sur mon parcours 5'
- Contexte aéronautique: SHM stratifiés / Diagnostic matériaux innovants 15'
- Robustesse des méthodes classiques d'identification modale pour le SHM 10'
- Perspectives et collaborations 5' MAC OMA etc…

Politique de recherche

- Principes fondamentaux

– Lien formation-recherche

- conforter l'excellence des formations d'ingénieur de l'ISAE

– Constituer un centre international d'accueil et de formation de masters et de doctorat

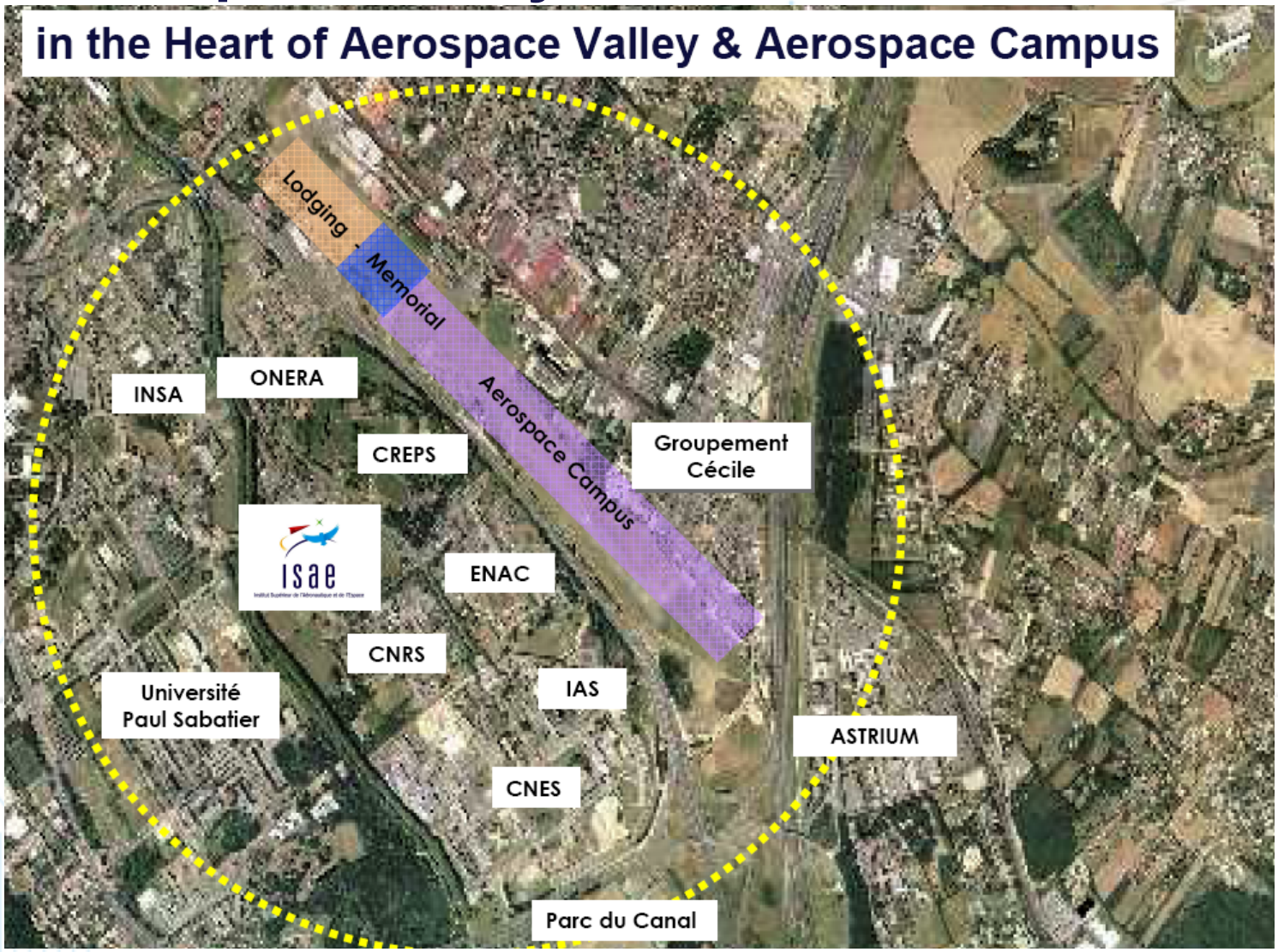
- Articulation entre capacités propres et partenariats forts

– Equilibre entre visibilité académique et proximité des finalitées industrielles

- Assurer le rayonnement scientifique : connaissances et échanges scientifiques
- Développer des partenariats avec les milieux institutionnel, industriel et économique

– Dominante forte aéronautique, spatial, Sys embarqué ;

Aerospace Valley



joseph.morlier@isae.fr

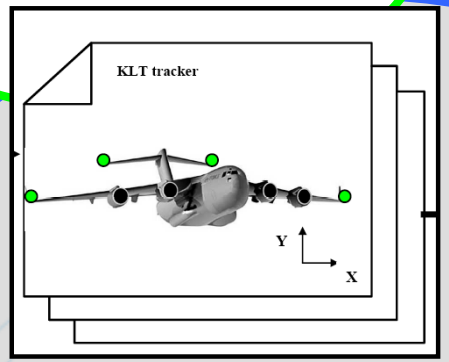
Depuis 2006 Professeur Associé ISAE Campus SUPAERO
Enseignement en PC/BE
UF Mathématiques: Calcul scientifique/ Matlab/ Optimisation
UF Mécanique: Calcul de structures, dynamique, Elements Finis, CAO
Projets Pluridisciplinaires en aéronautique

Qualification MCF en section CNU 60
(Mécanique, Génie Mécanique et Génie Civil)
Qualification MCF en section CNU 61
(Génie informatique, automatique et traitement du signal)

Docteur Es sciences (Diagnostic de structures par analyse modale et traitement du signal)
DEA en Traitement du Signal/Image (ENSEIRB)
Ingénieur GEII (Bordeaux 1)

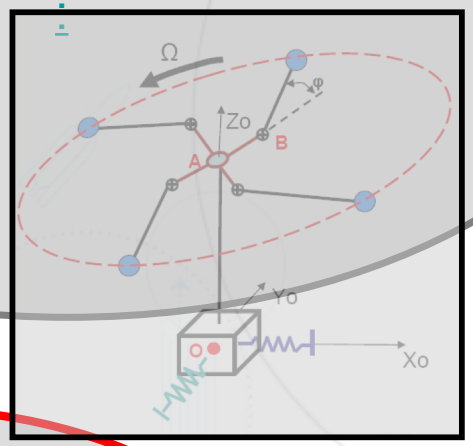
Intelligent sensors

Image processing
Embedded piezocomposites



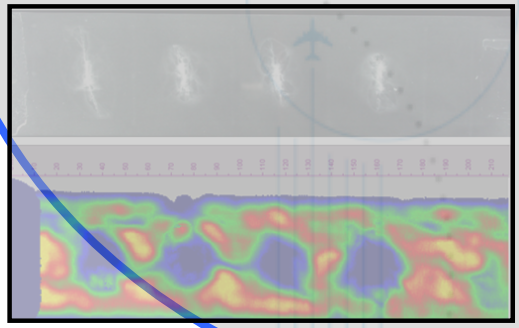
Nonlinear dynamics

GVT Rotor models and tests



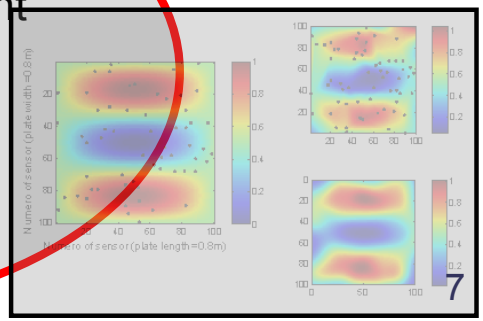
Structural Monitoring

Structural dynamics
FEM model update
Damage in composites



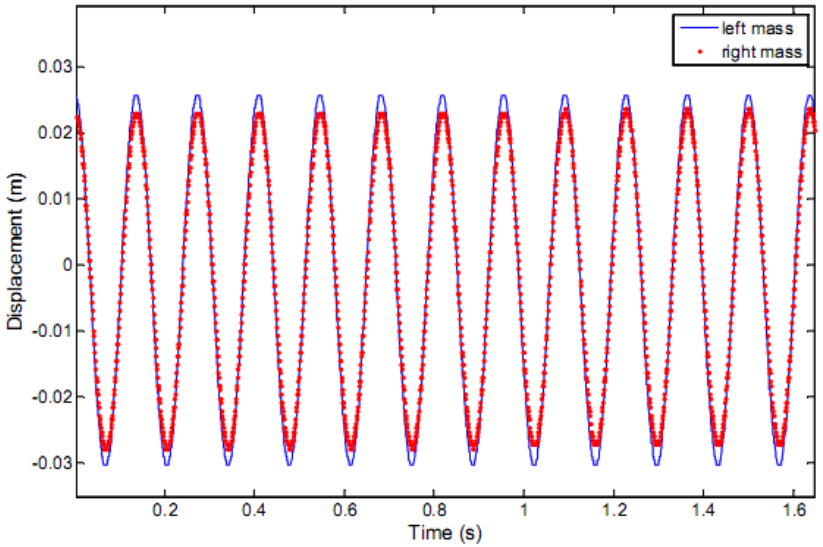
Signal processing, DOE

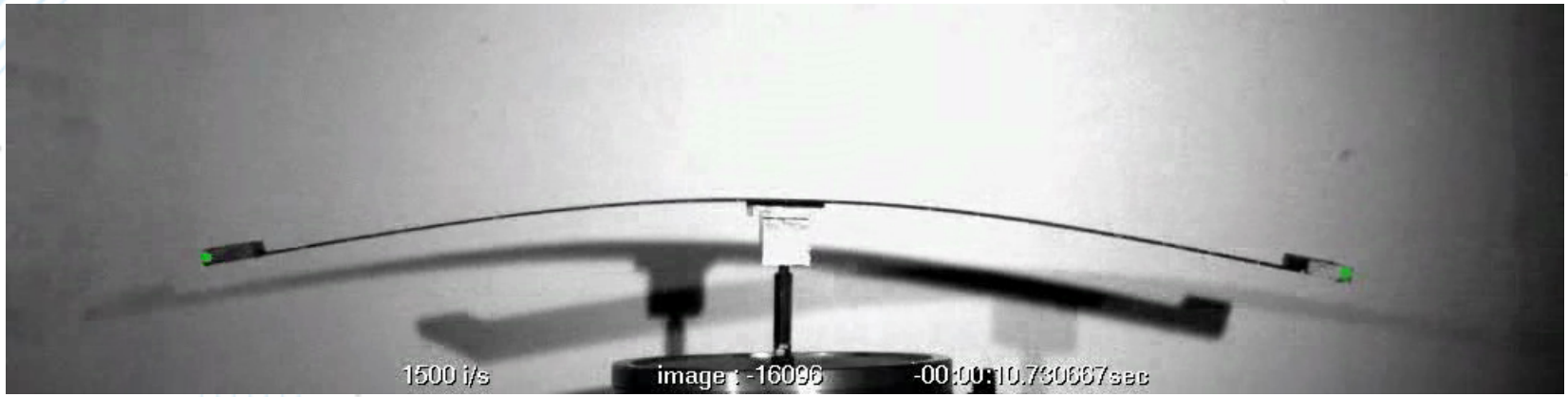
Optimal sensor placement
Transient Output only
Identification



Intelligent sensors

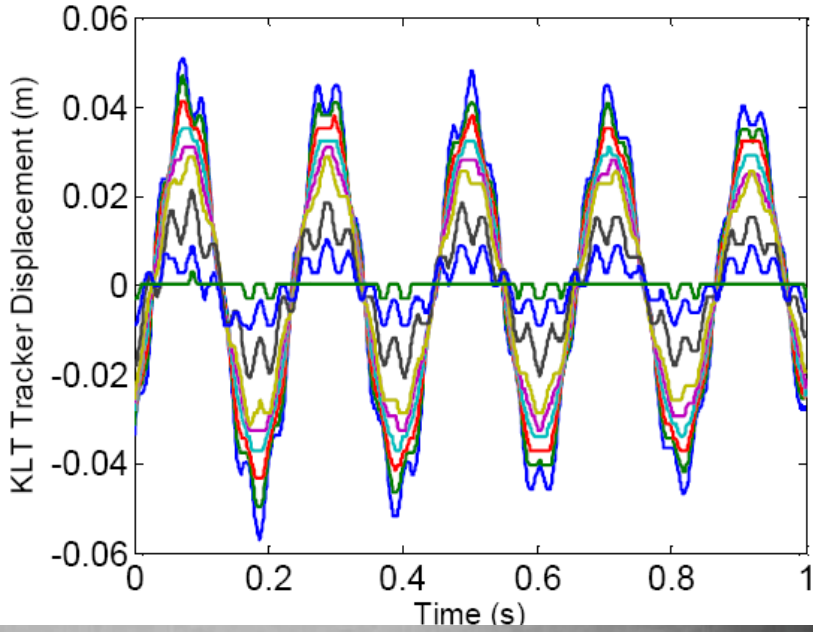
- Use of motion tracking algorithm (KLT) to measure the structural vibration using High Speed Camera





Intelligent sensors

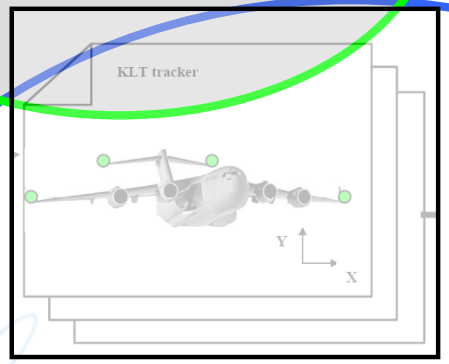
- Monitoring d'une pale d'hélicoptère
- Mise en place « facile » de Capteurs virtuels KLT





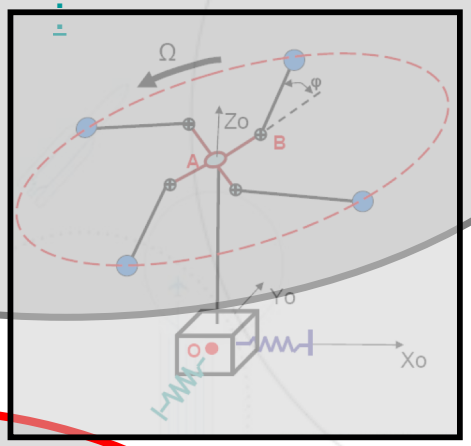
Intelligent sensors

Image processing
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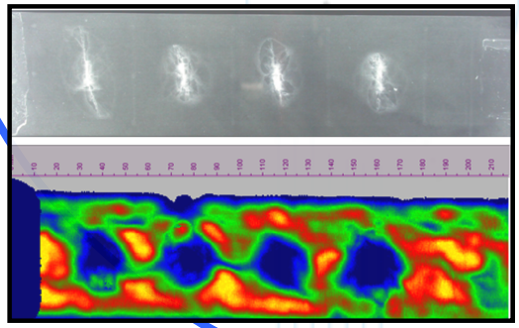
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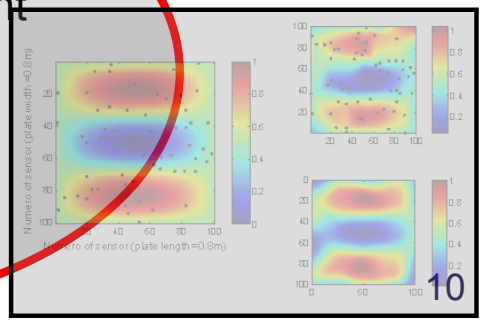
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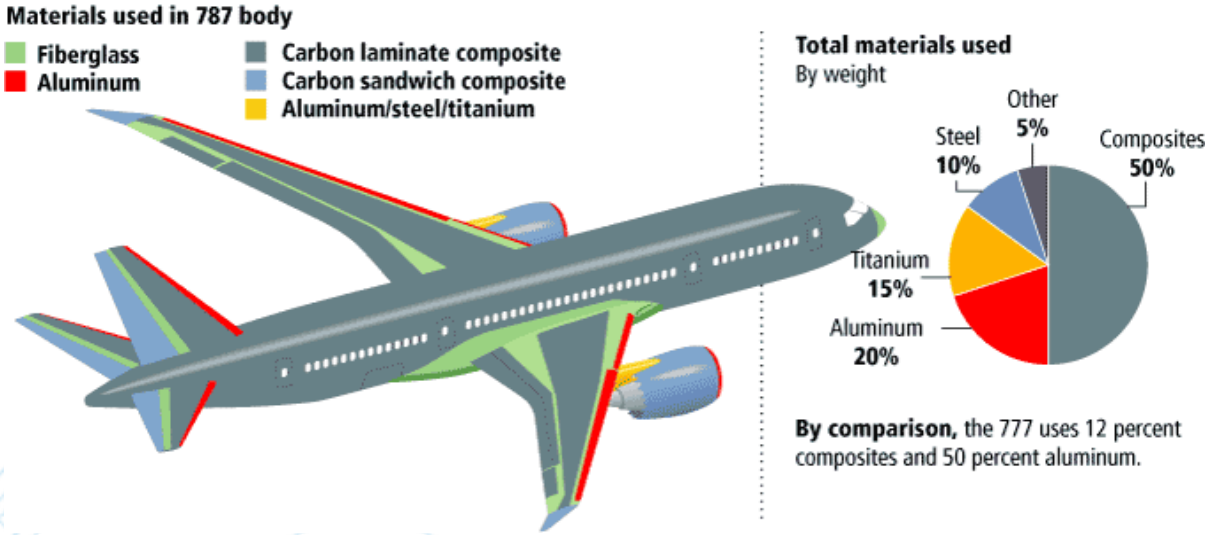


Signal processing, DOE

Optimal sensor placement
Transient Output only
Identification



SHM in Smart Structures (Composites)



Boeing 787

50% de la Structure

En Composites

➢ Pourquoi ?

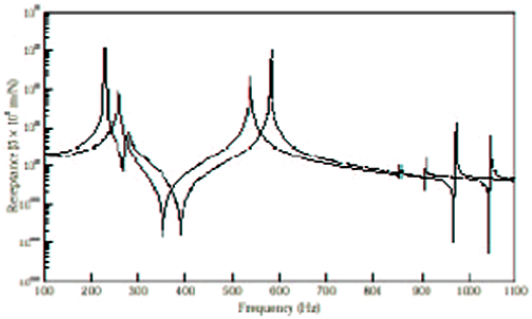
- ✓ Augmente la rigidité/tenue spécifique
- ✓ Réduit la masse

➢ Endommagement?

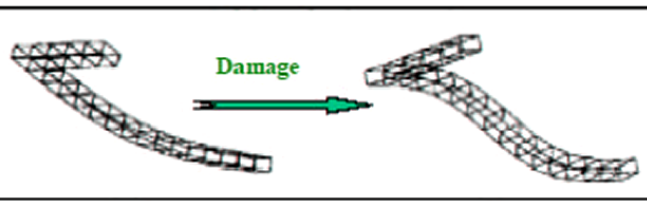
- ✓ Contraintes résiduelles (fabrication)
- ✓ Charges en opération
- ✓ Impacts divers (birdstrike, ice …)

Méthodes vibratoires

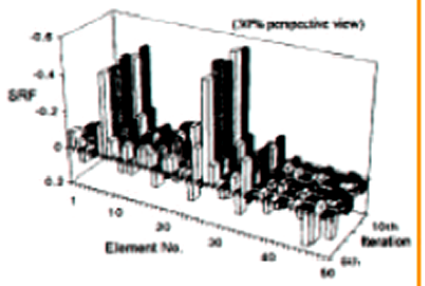
Natural frequency shifts



Mode shape changes



Flexibility matrix analysis



DYNAMIC RESPONSE METHODS

Mode shape derivative or curvature changes

Φ_D Φ

$$\Phi'' = \frac{\Phi_{i+1} - 2\Phi_i + \Phi_{i-1}}{\Delta h^2}$$

differences

DAMAGE DETECTION

Update of structural model parameters

TEST UNDAMAGED STRUCTURE → UPDATE UNDAMAGED FEM

FEM MODEL

DAMAGE DETECTION ← ITERATIVE ALGORITHMS

TEST DAMAGED STRUCTURE → UPDATE UNDAMAGED FEM

Notre Philosophie en SHM

Damaged Specimen

?

EMA

Modal Analysis for estimating:
- Natural frequencies
- Mode shapes

Damping Ratio

Frequency Response Analysis:
- $x(\Omega) = H(\Omega)\, f(\Omega)$

Magnitude Phase

Level 2 : LOCALISATION

NDT

TO

MU

Level 1 : DETECTION

FEA

Baseline FE Model Updated with undamaged specimen modal data

Modal Analysis for estimating:
- Natural frequencies
- Mode shapes

Damping Ratio

Frequency Response Analysis:
- $x(\Omega) = H(\Omega)\, f(\Omega)$

Magnitude Phase

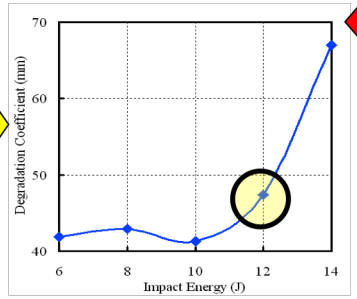
Level 3 : IDENTIFICATION

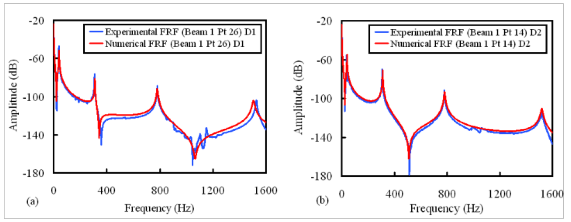
Model Update using localised damaged zones and optimization

Level 4 : GENERALIZATION

DATABASE OF EXPERIMENTAL / NUMERICAL RESULTS

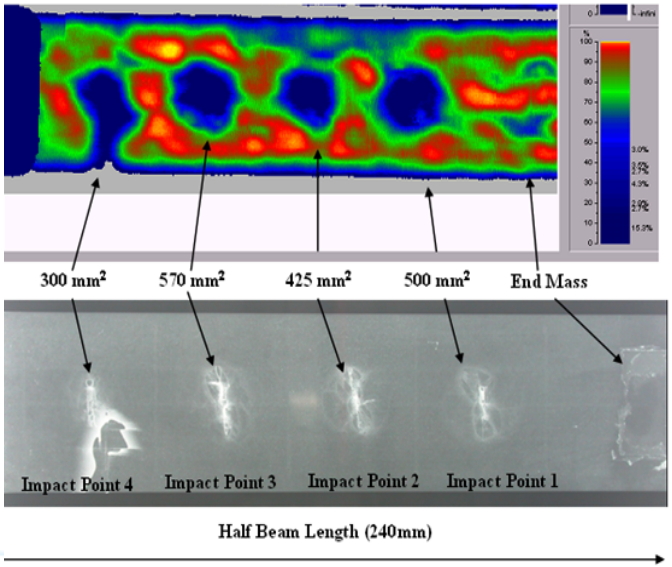
Level 4 : QUANTIFICATION





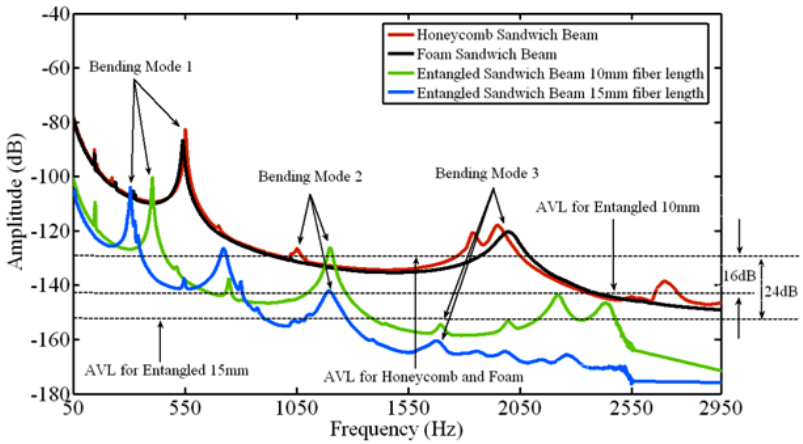
Diagnostic Vibratoire

- pour comprendre : Le lien entre endommagement (zone de délaminag et augmentation d'amortissement (zone de friction)



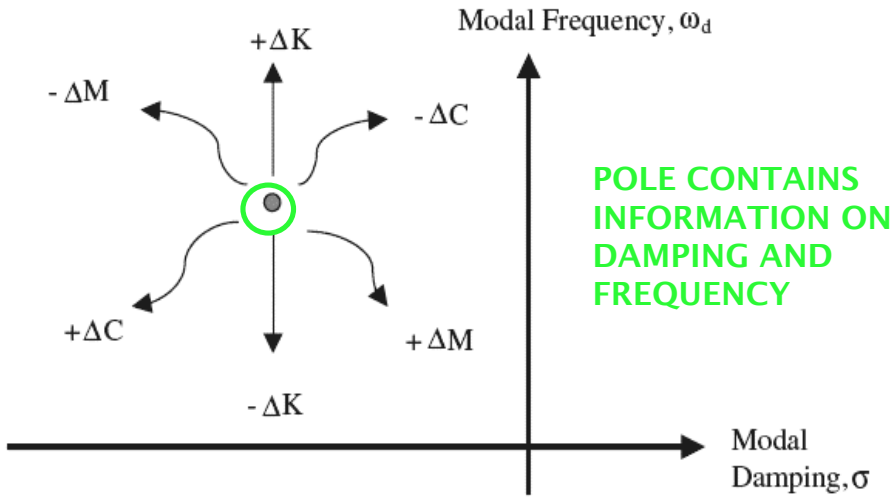
Damage zones:
local loss of rigidity
(decrease in frequency)
+increase the surface of friction
(increase in damping)
due to delamination

- Pour comparer les performances de nouveaux matériaux / composites/sandwiches



Techniques de SHM

- Ultrasonic testing
- Radiography
- Eddy current testing
- Liquid penetrant testing
- Infrared thermography
- Visual testing (optical)
- Vibration testing

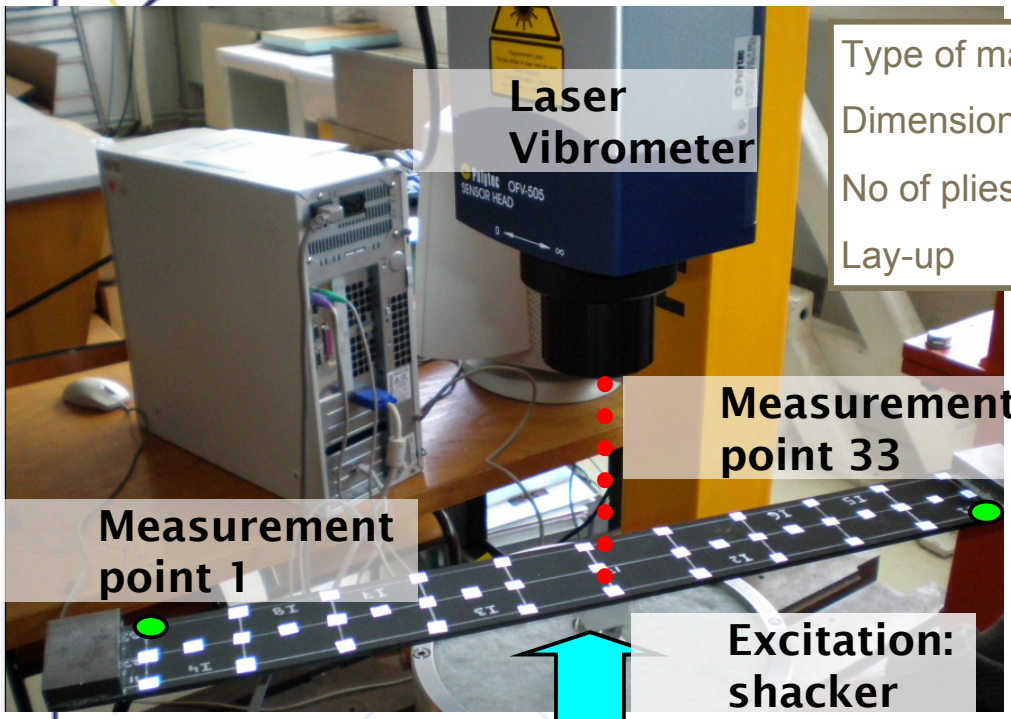


Purpose of vibration based damage detection

Damage in a structure changes the modal parameters in the following way:

- ✓ Decrease in natural frequency
- ✓ Increase in damping ratio

Vibration Tests: Testing Methodology



Type of material	T300/914
Dimensions of the beam	480 x 50 x 3 mm
No of plies	24
Lay-up	[0/90/45/-45]3s

➢ **Acquisition Parameters for both BR and SD excitations)**

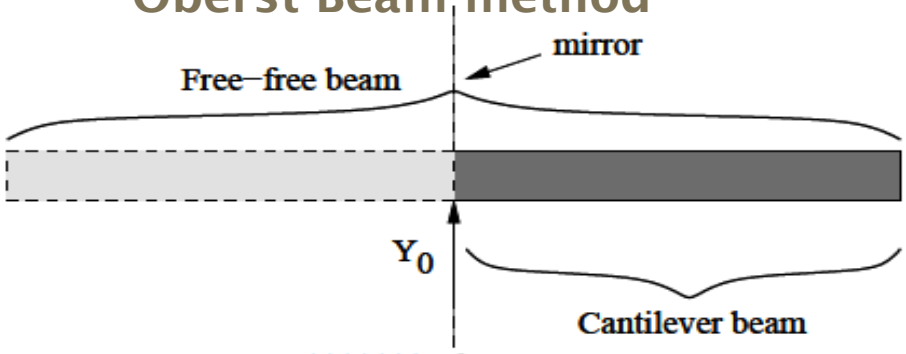
✓ Frequency Resolution = 0.25Hz

✓ Excitation level = 1N

✓ Same number of measurement points for each beam (33 symmetric points)

✓ As the damages are symmetrical, We can compare the sum of FRF

Vibration test based on Oberst Beam method



Damping Estimation difficult ?

Use 2 Modal Parameter Estimators as previous study show us damping **is difficult to estimate** (Frequency is reliable)

- ✓ **POLYMAX** (frequency domain – LMS– Burst random)
- ✓ **POLYREFERENCE** (time domain –B&K – Sine Dwell take into account NL)

Both algorithms are based on least-squares optimization on 33 FRFs

Aim is to calculate the best optimum value of pole for each mode

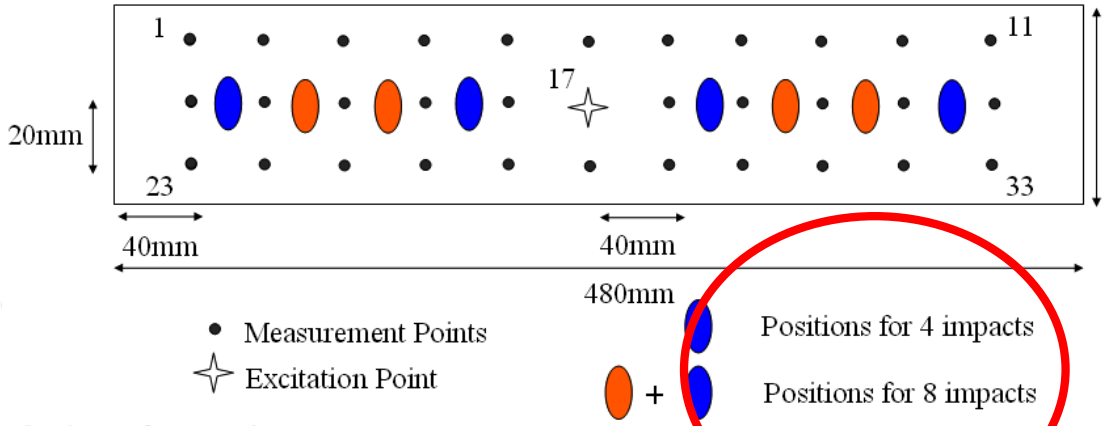
Experiments on 5 identical composites beams

➢ Modal Test Parameters

Type of Excitation	Burst Random
Resolution	0.25 Hz
Frequency bandwidth	0-1600 Hz
Modes of interest	First four bending modes

➢ Impact Test Parameters

Beam No	Energy of Impact (J)
1	6
2	8
3(BVID)	**10 (0.55mm)**
4	12
5	14

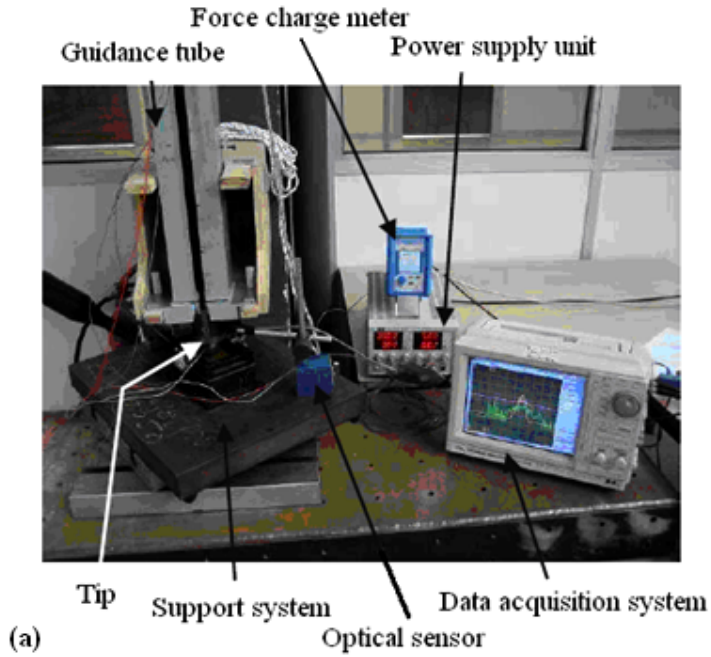


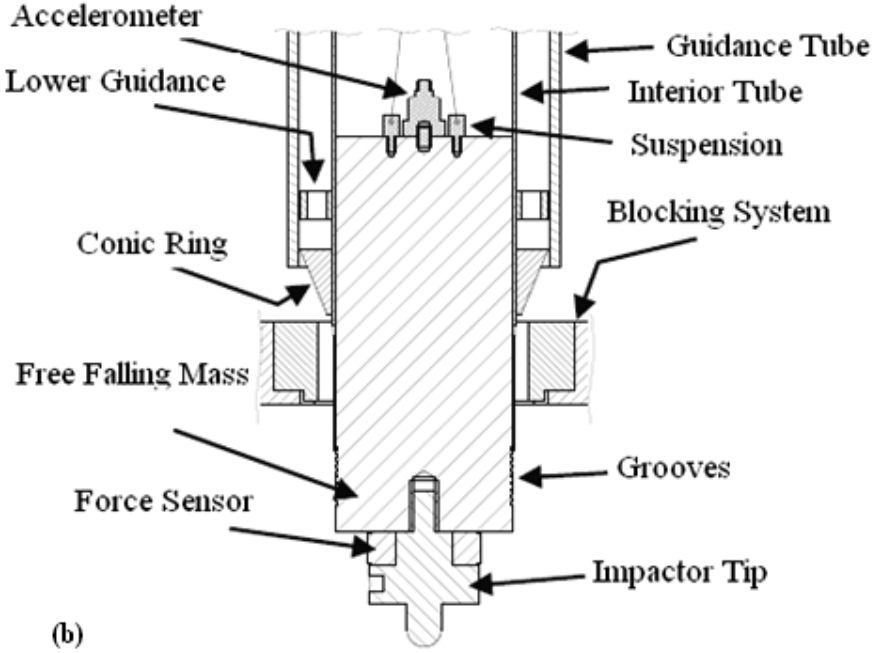
Parameters of the 5x2 Full Factorial DOE

Vibration tests carried out after each of the three states i.e., Undamaged (UD), Damage at 4 points (D1) and at 8 points (D2)

Impact Tests

- Impact tests are carried out by a drop test machine
- Impactor has a hemispherical head with a radius of 12.7mm
- Beams are clamped at four ends during impact

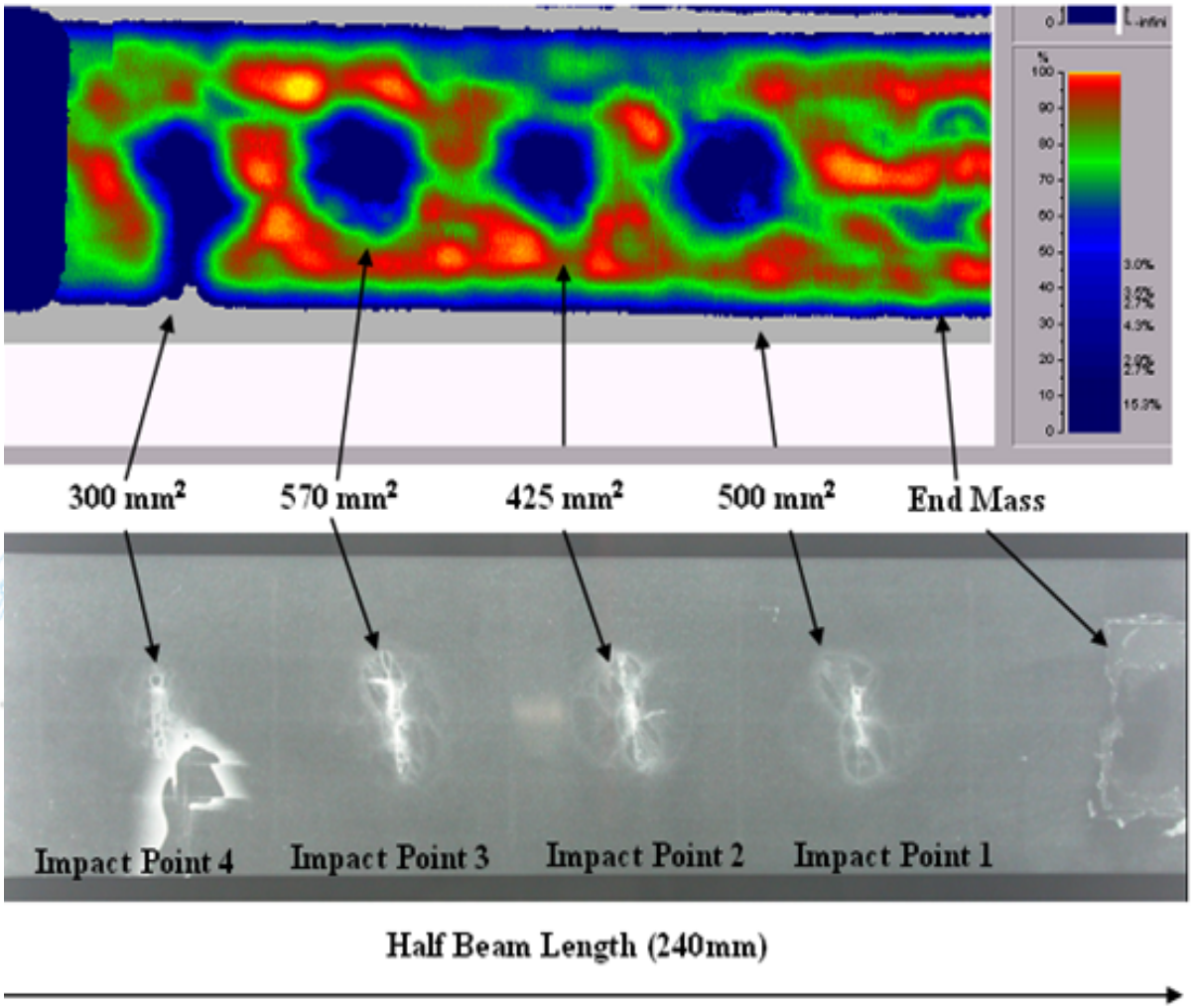




Impacts carried out around the BVID limit

0.5-0.7mm of indentation depth just after impact

NDT results for impact tests (repetitivity)

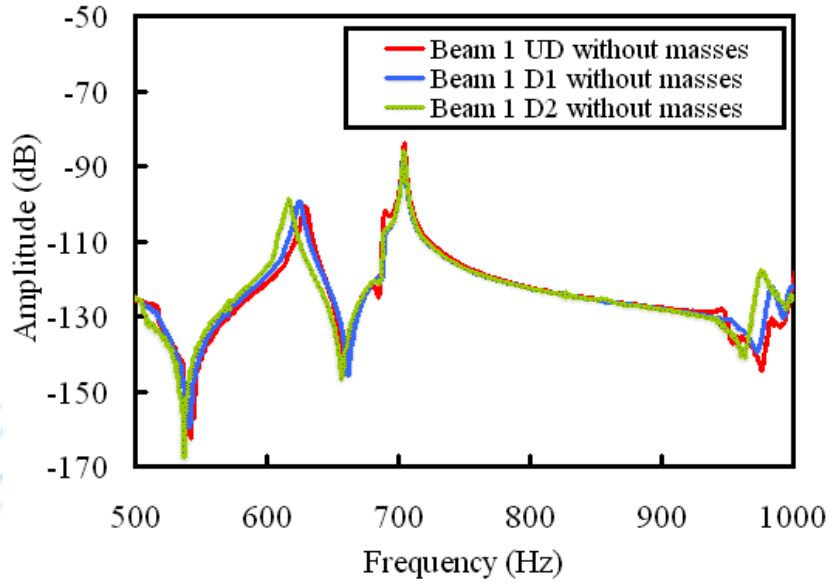


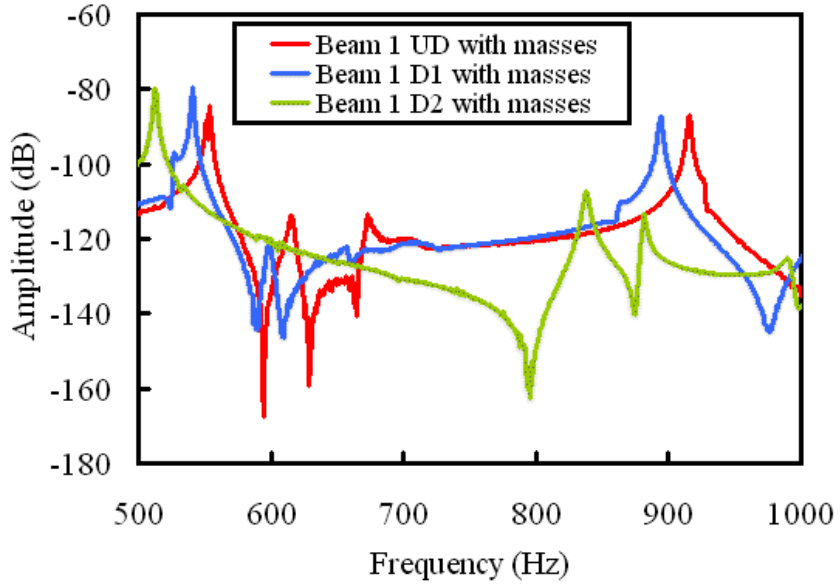
C_SCAN

Damage zones:
local loss of rigidity
(decrease in frequency)
and
increase the surface of friction
(increase in damping)
due to delamination

RADIOSCAN

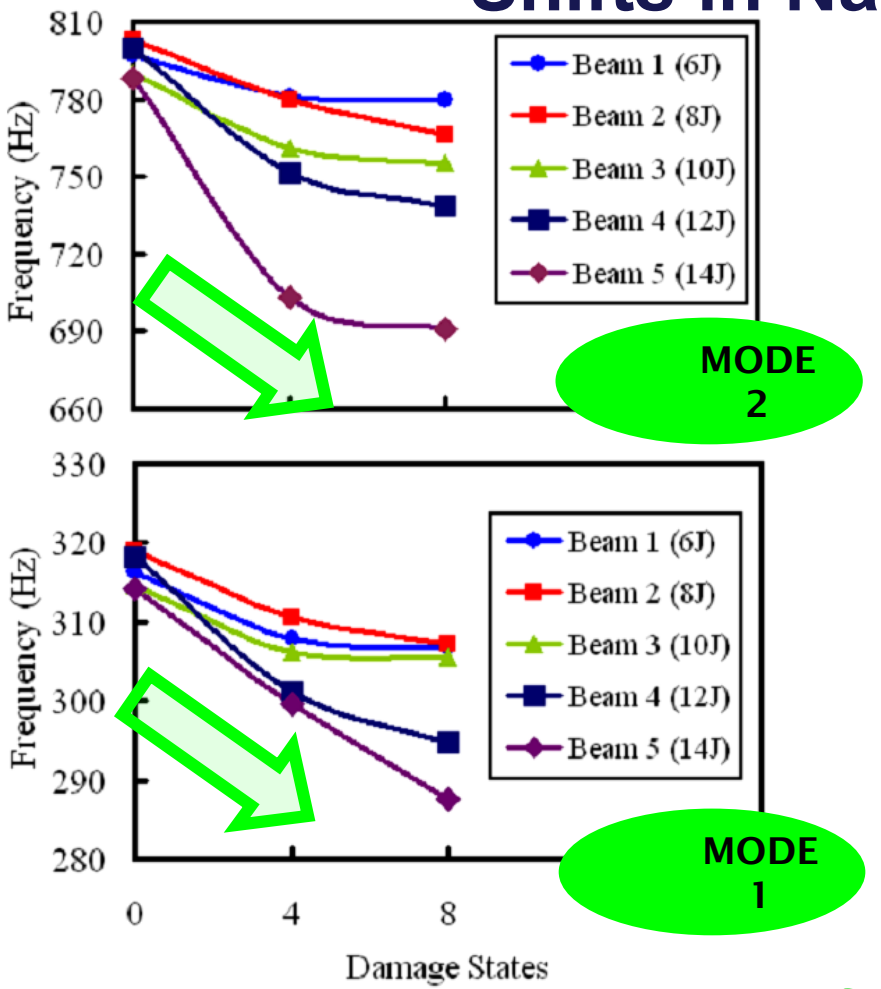
Significance of End-Masses

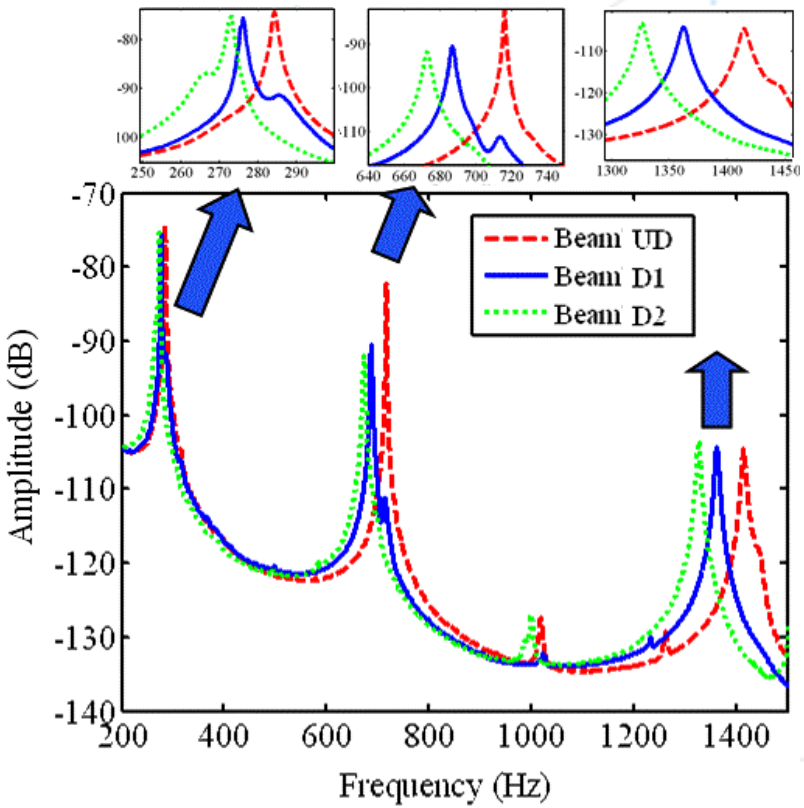




Shift in modal parameters is enhanced with end-masses (add shearing effect)

Shifts in Natural Frequency



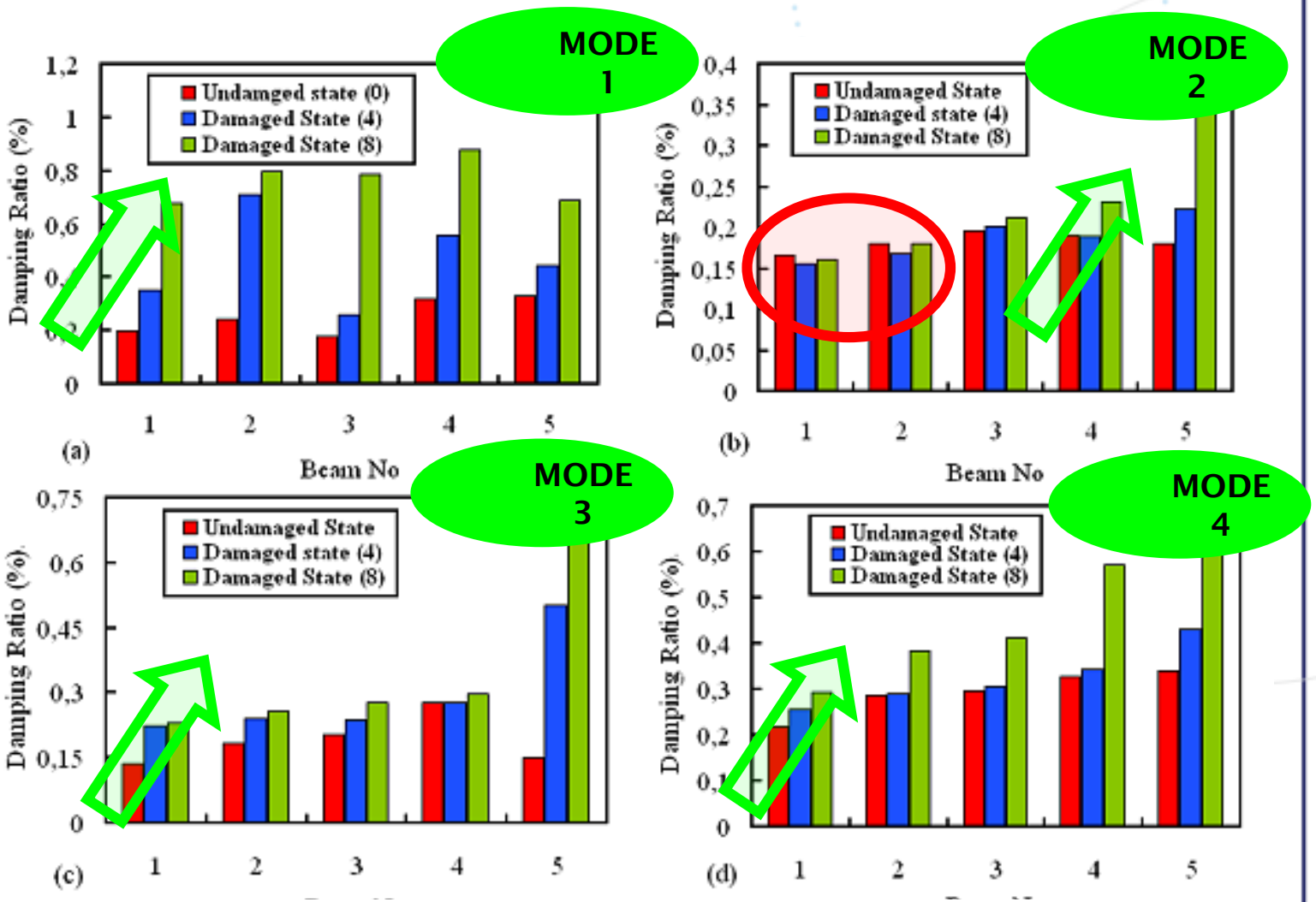


For all modes: Decrease in frequency increases with damage

Shift in frequency is higher for higher modes

Composite Laminates

➢ Shift in Damping Ratio



Generally damping increase with damage but sometimes not consistent with damage

Better results with Sine Dwell excitation (non-linearity effects)

DOE: influence of key parameters
2 factors : energy of impact and density of damage

- **Which Modal Parameter is more sensitive to damage ?**
  - ✓ Change in natural frequency = Less than 12%
  - ✓ Change in damping ratio = Up to 200 %

- **Which Design Factor is more sensitive to modal parameters ?**

Design of Experiments

- ✓ Energy of Impact = 6J to 14J
- ✓ Density of Damage = 0 (UD), 4 (D1) and 8 (D2)

By comparing the t-ratios it was found that Energy of Impact is Globally (2nd, 3rd, 4th mode) the more sensitive to the response (modal parameters frequency and damping ratio)

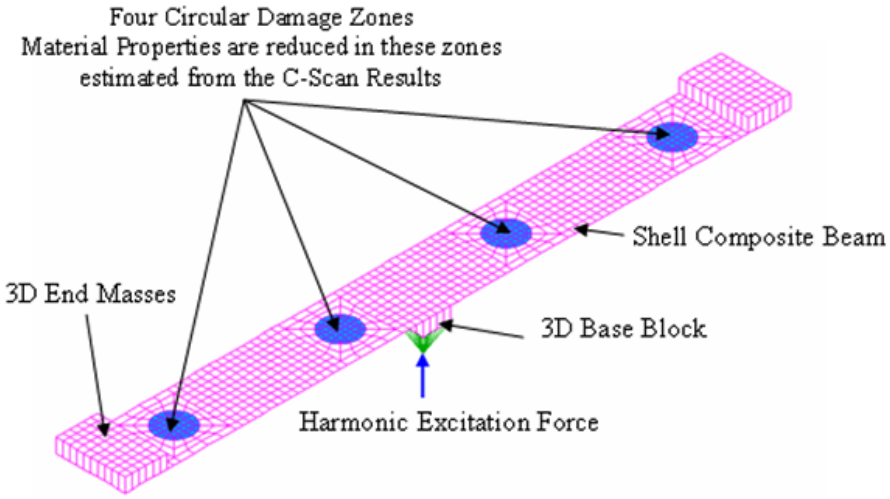
Composite Laminates impacted around BVID

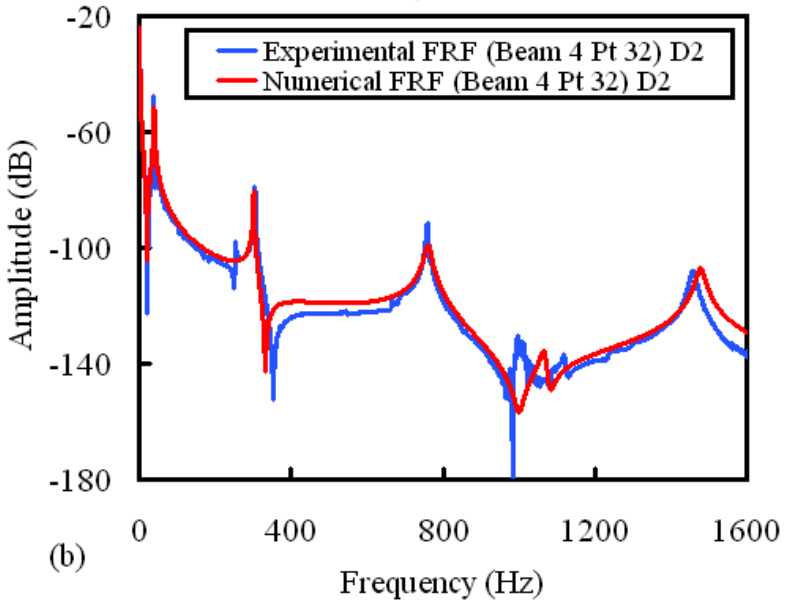
➢ **Conclusion**

Natural Frequency decreases and damping increases with damage

- ✓ Decrease in frequency consistent with damage unlike damping
- ✓ Damping more sensitive to damage
- ✓ Energy of impact more sensitive to the response (modal parameters)

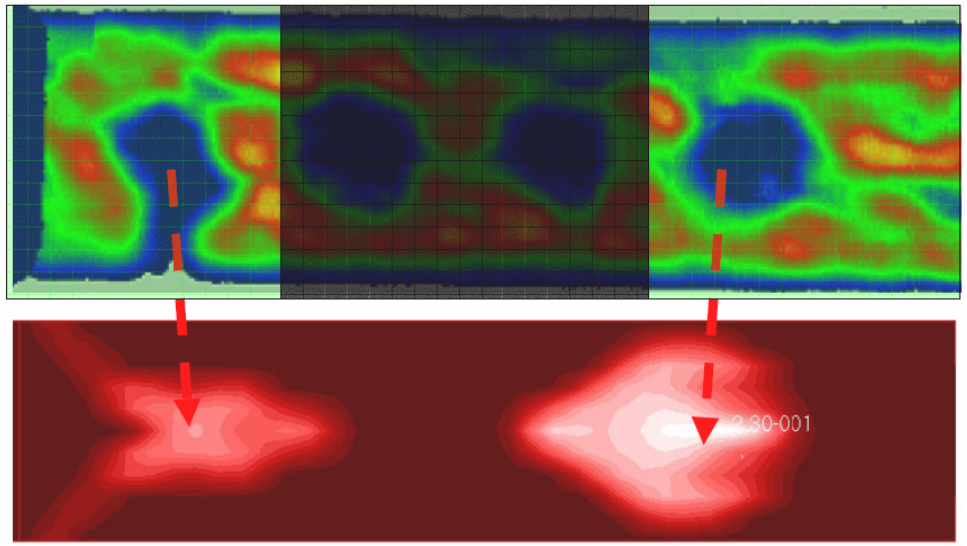
FEM updating tool

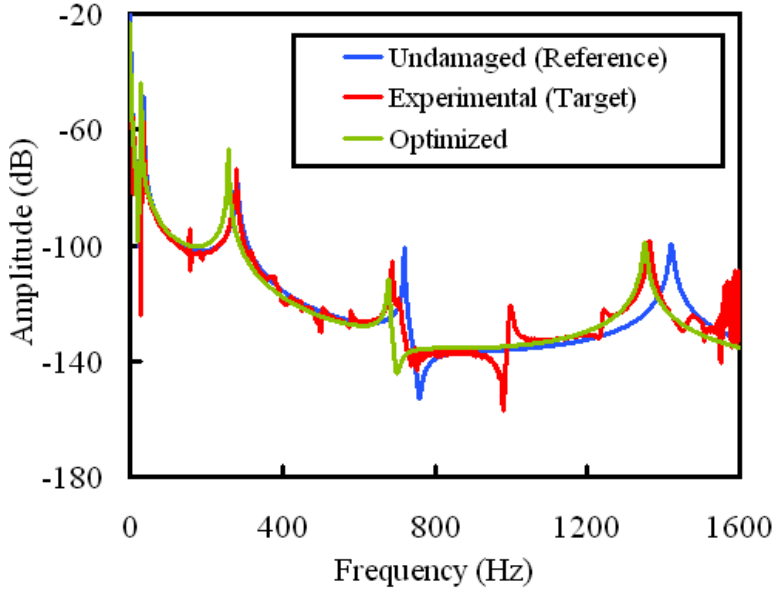




Comment localiser ?

➢ Damage localization using topology optimization



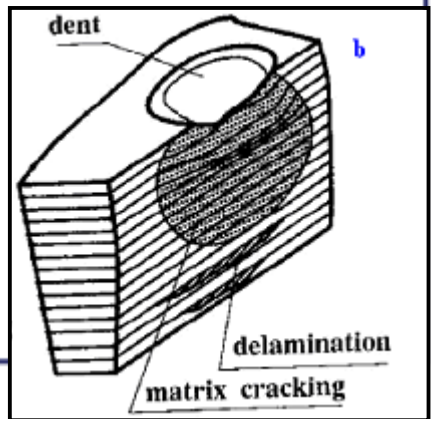


➢Vary the impacts: non-symmetric impacts, different shapes of impactor heads

➢ to study the effect of different types of damage on modal parameters

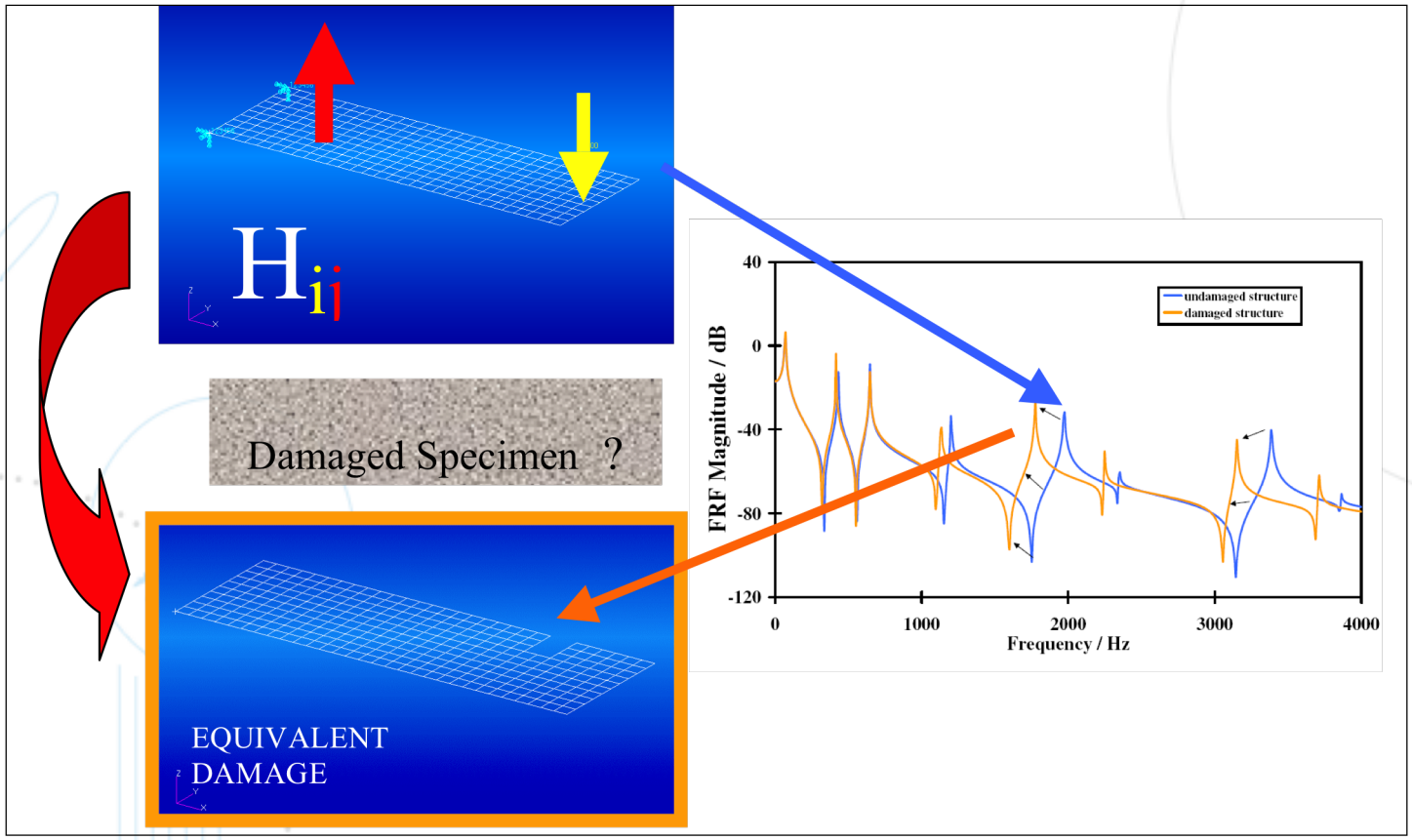
➢ Precise local modelling of the damage phenomenons
(ply by ply, shape of the delamination, , matrix cracking etc).

Application: impact detection, localisation and energy estimation on aircraft specific structure (door panel)



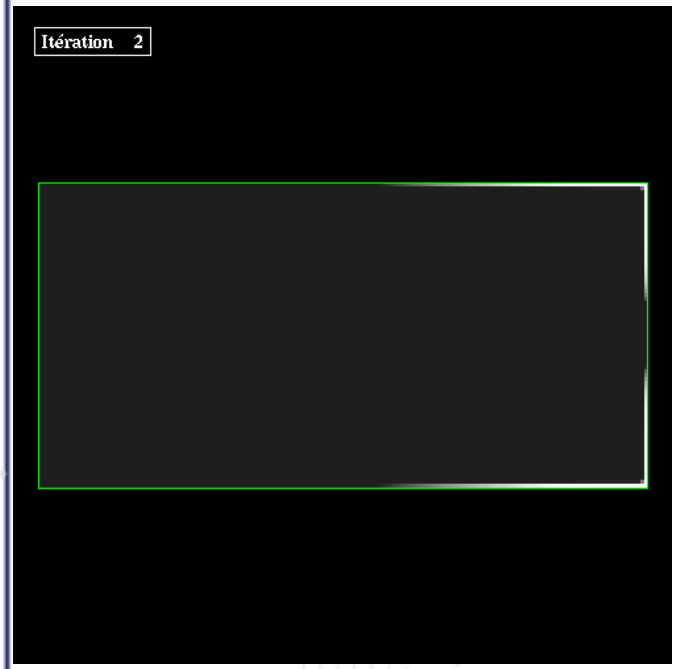
Damage localization by Topology Optimization

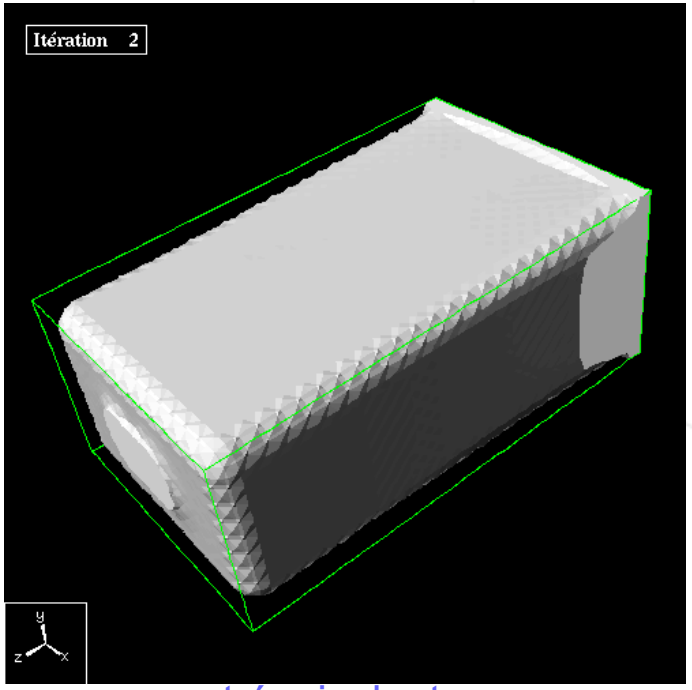
L'outil d'optimisation topologique estime un endommagement équivalent par minimisation de la différence entre un état supposé sain (modèle EF) et le spécimen endommagé (PFE d'Hanno Niemann)



Optimisation topologique (TO)?

Utilisation classique (statique)
La recherche de la distribution optimale de masse
dans la *domaine de design* en conservant une rigidité maximale
(minimisation de la compliance)



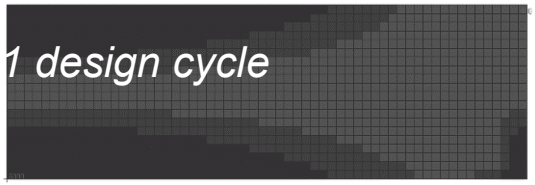


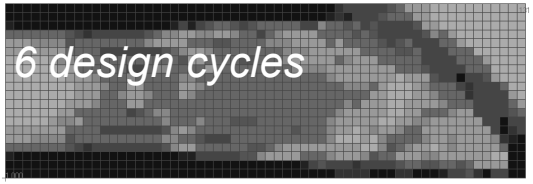
En fait on estime un modèle d'endommagement équivalent
par minimisation de la différence entre un état supposé sain
(modèle EF) et le spécimen endommagé (PFE d'Hanno Niemann)

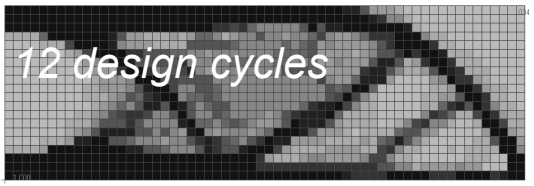
Principes de l'Optimisation Topologique

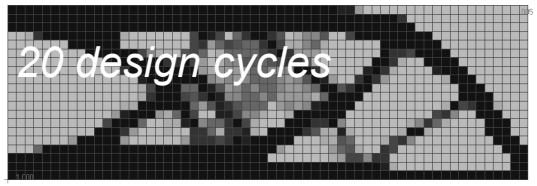
- Les variables de conception $\chi_e = \frac{\rho_e}{\rho_0}$ soumis à $0 \leq \chi_{min} \leq \chi \leq 1$.
- Mise à jour de la propriété E de l'élément pour altérer sa rigidité : $E_e = \chi_e^p E_0$

Utilisation classique (statique) : la recherche de la distribution optimale de masse dans la domaine de design en conservant une rigidité maximale (minimisation de la compliance).







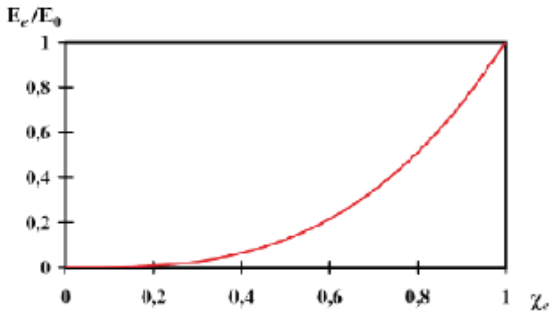


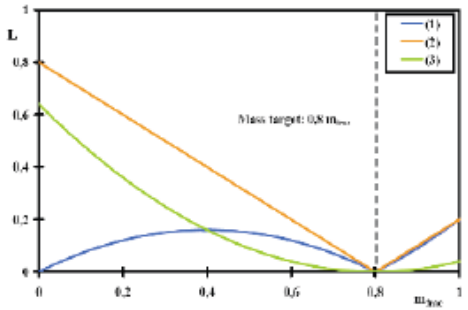
Application à la détection d'endommagements

$$\min_{\chi_e, \chi_{\min} \le \chi_e \le 1} L = \min_{\chi_e, \chi_{\min} \le \chi_e \le 1} \sum_{e=1}^{N_e} \chi_e (1 - \chi_e)$$

Adaptation à une formule pseudo-objective incluant

- 2 paramètres de pénalité sont utilisés pour obtenir un résultat N&B (seuillage pour éliminer les valeurs intermédiaires)
- Paramètres de masse cible à régler en fonction de l'endommagement $E_e = \chi_e^p E_0$ et $m_e = \chi_e^p m_0$

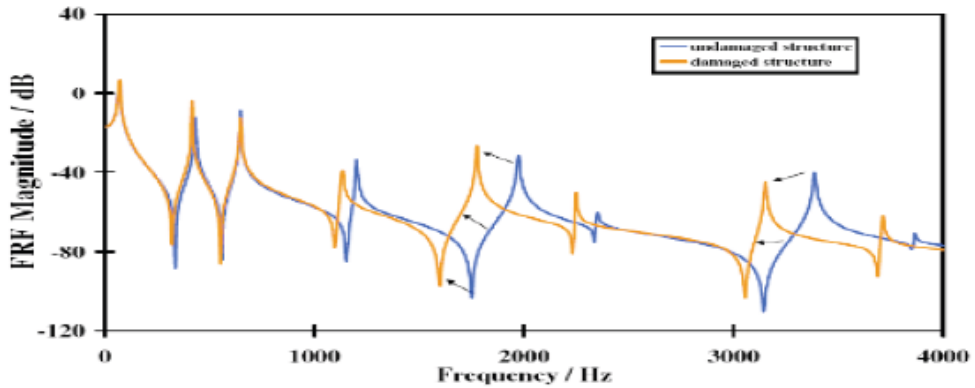




Formulation du problème de localisation d'endommagements par impacts (BVID)

2 types de contraintes

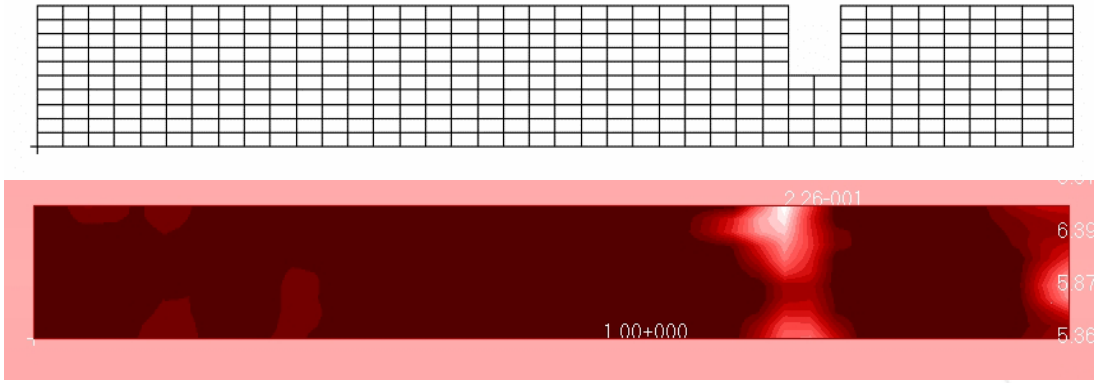
- Matching des fréquences $g_i^w = (w_i^2 - \overline{w}_i^2)^2$ pour $i = 1 \ldots n$
- Matching des FRF $g_j^H = (H_{kl}(\Omega) - \overline{H}_{kl}(\Omega))^2 \leq \varepsilon_H$ pour $i = 1 \ldots N$.



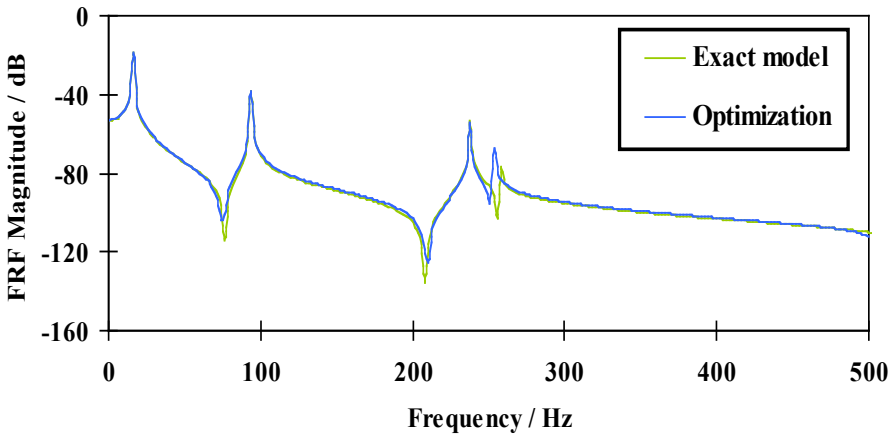
Nastran utilise la sensibilité du modèle EF pour trouver le gradient le plus important afin d'initialiser l'optimisation (premier élément altéré).

Résultats de simulation

- Poutre avec un crack (2d):



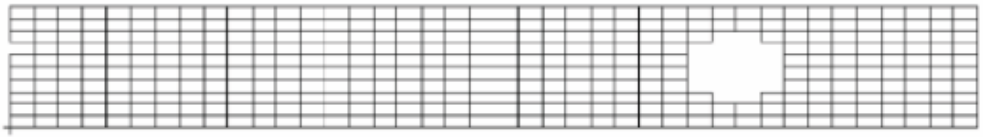
Mode	Natural Frequencies / Hz	
	Model	Optimization
1	16	16
2	94	94
3	238	238
4	256	254
5	257	257



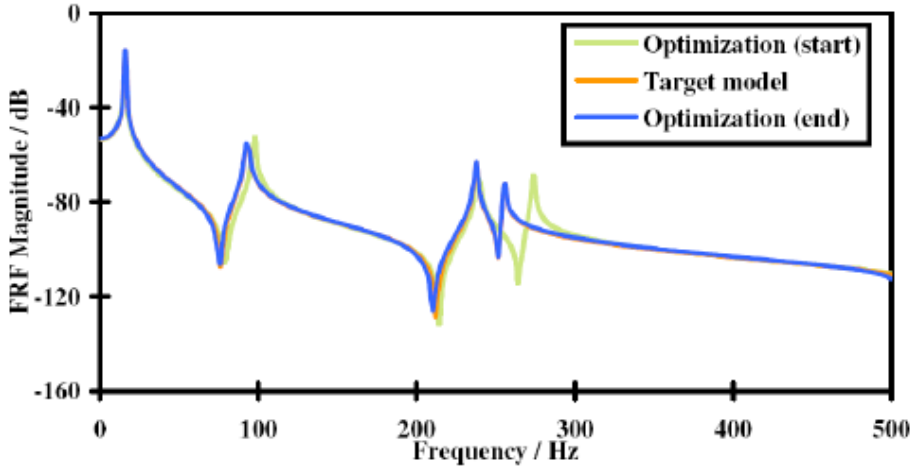
Utilisation d'un seuillage



(a)

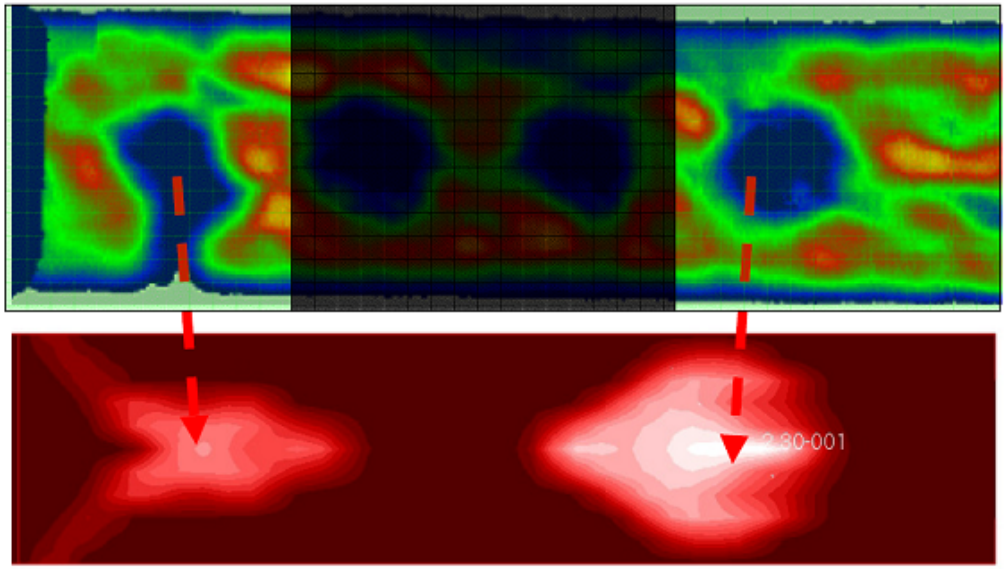


(b)

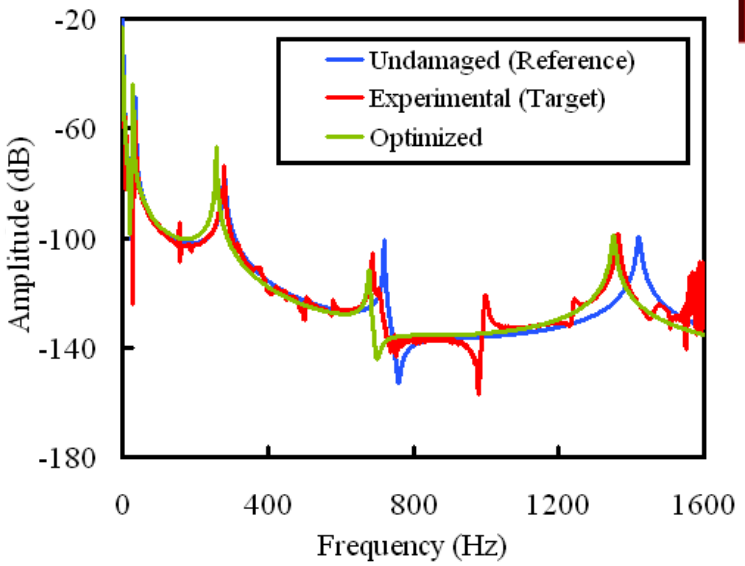


Résultats Nieman et al, MSSP 2009:
(Calcul sur stratifié homogénéisé) Comparaison avec les résultats C-scan:
le défaut est un changement local de rigidité

- C_scan



- Optimisation



	Natural Frequencies / Hz	
Mode	Model	Optimization
1 (1st bending)	36	30
2 (2nd bending)	157	148
3 (1st torsion)	279	259
4 (3rd bending)	687	679
5(2nd torsion)	999	1001
6 (4th bending)	1363	1351

Objectives of this Work

To Develop a Composite Sandwich Beam with Entangled Fiber Core possessing:

- **Enhanced Damping Characteristics**
- **Good Resistance against Impact**

Comparison with Standard Sandwiches with Honeycomb and Foam Cores in order to compare:

- **Elastic and Shear Modulus (Static Properties)**
- **Modal Parameters especially Damping (Dynamic Properties)**
- **Resistance against Impact**

Justification of our Approach

Innovated Sandwiches used for enhanced damping and better impact toughness

- **Sandwiches with visco-elastic layer**
- **Integrated core sandwiches**
- **Rubberized syntatic foam sandwiches**
- **Paper honeycomb sandwiches**

Composites = fibers + matrix

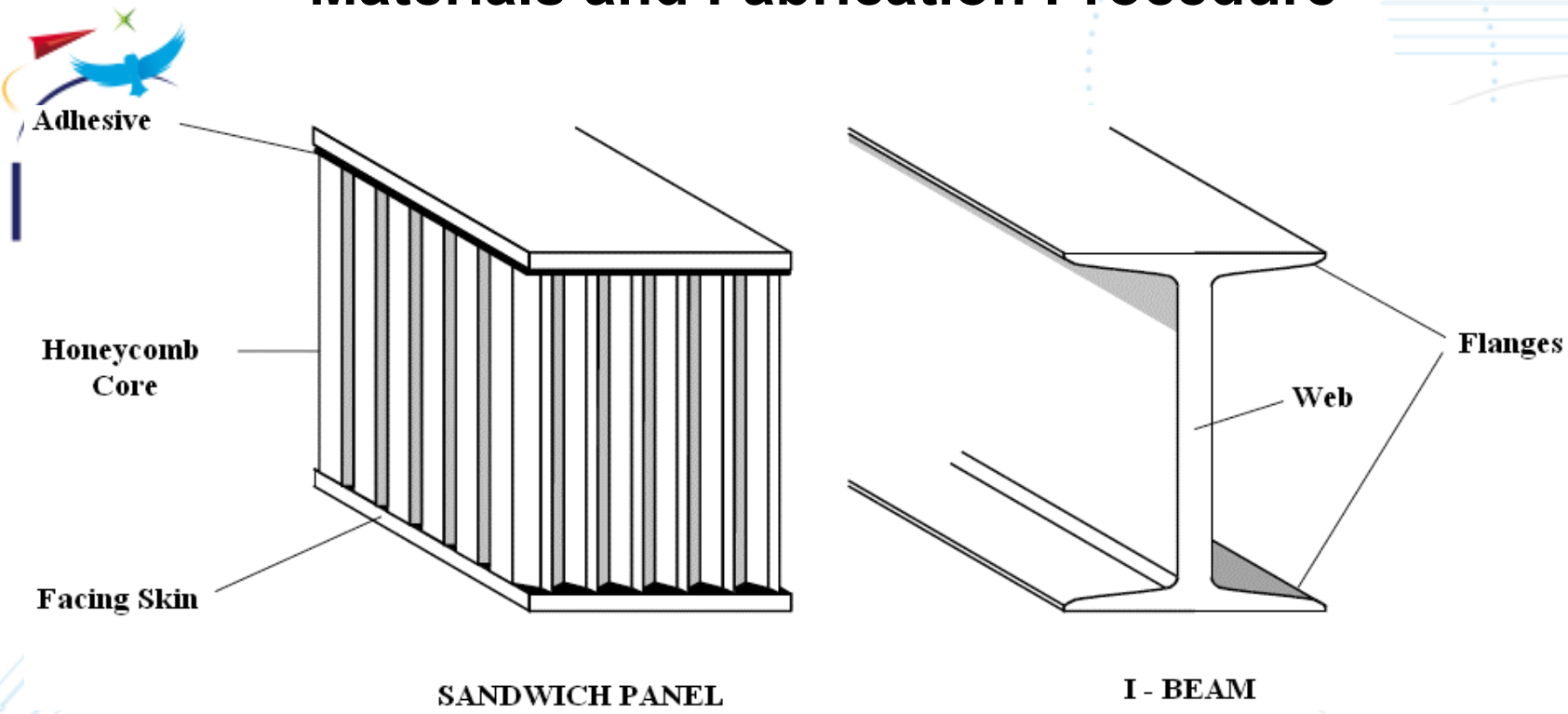
Not entangled sandwiches

Little Scientific Literature available related to entangled sandwich materials for enhanced damping and resistance against impact

- **Entangled Steel Fiber Cores [1]**

[1] Dean J, Fallah AS, Brown PM, Louca LA, Clyne TW. Energy absorption during projectile perforation of lightweight panels with metallic fibre cores. *8th International Conference on Sandwich Structures (ICSS 8), Porto, 2008*.

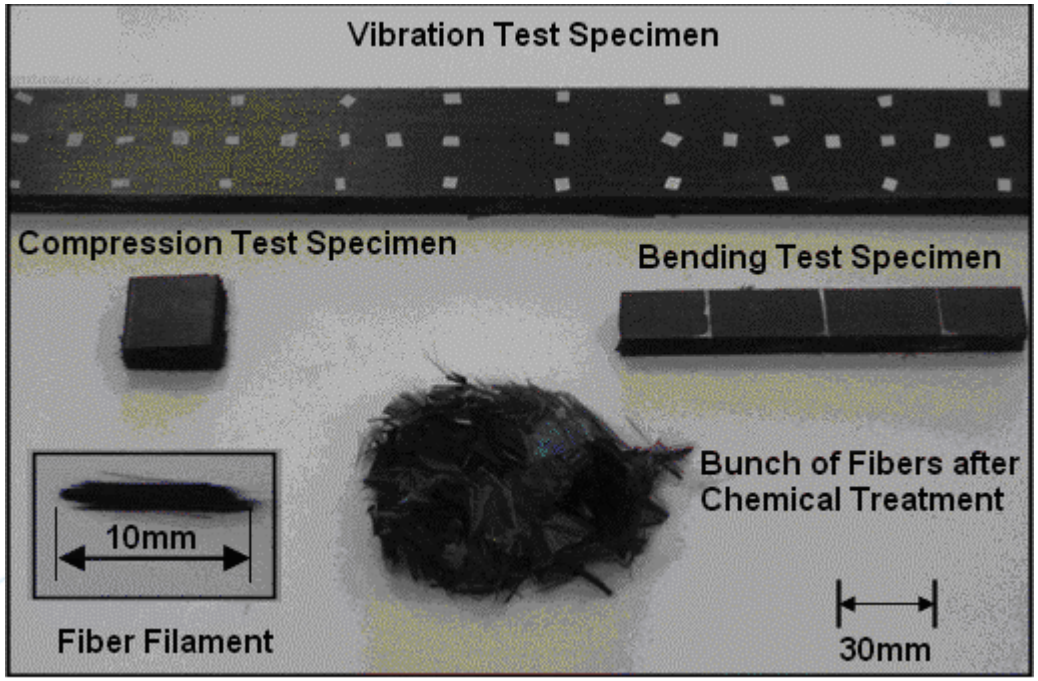
Materials and Fabrication Procedure



Advantages of Replacing the I-Beam Web by a Core

- Core resists the shear loads
- Core increases the stiffness of the structure
- Core gives continuous support to the flanges (facing skins) to produce a uniformly stiffened panel

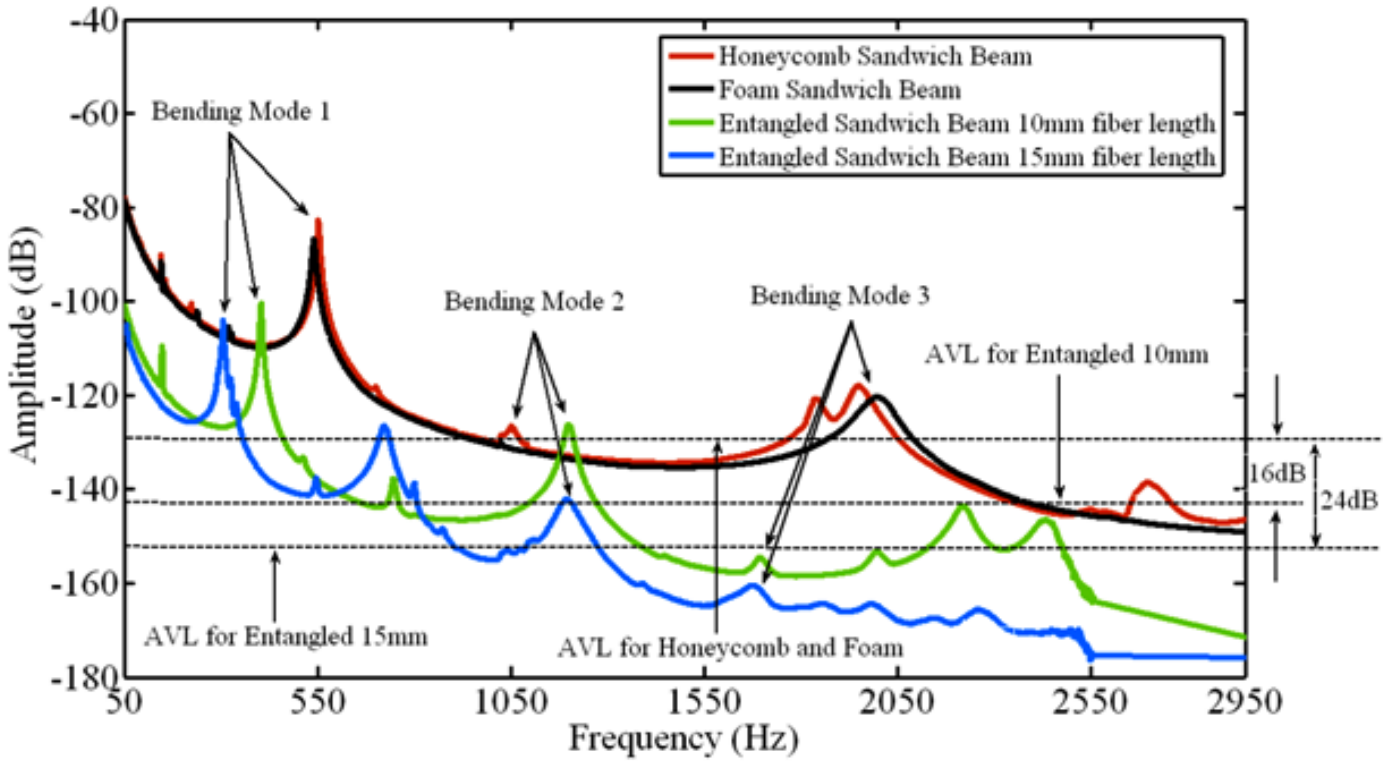
Fabrication of Carbon/Glass Fiber Entangled Beams



- Cutting of carbon/glass fibers (200 kg/m^3 fiber core density without resin)
- Chemical treatment of fibers followed by a separation by compressed air
- Vaporization (putting resin) of fibers
- Placing the vaporized fibers between the composite skins in a mold

Static and Dynamic Characterisation

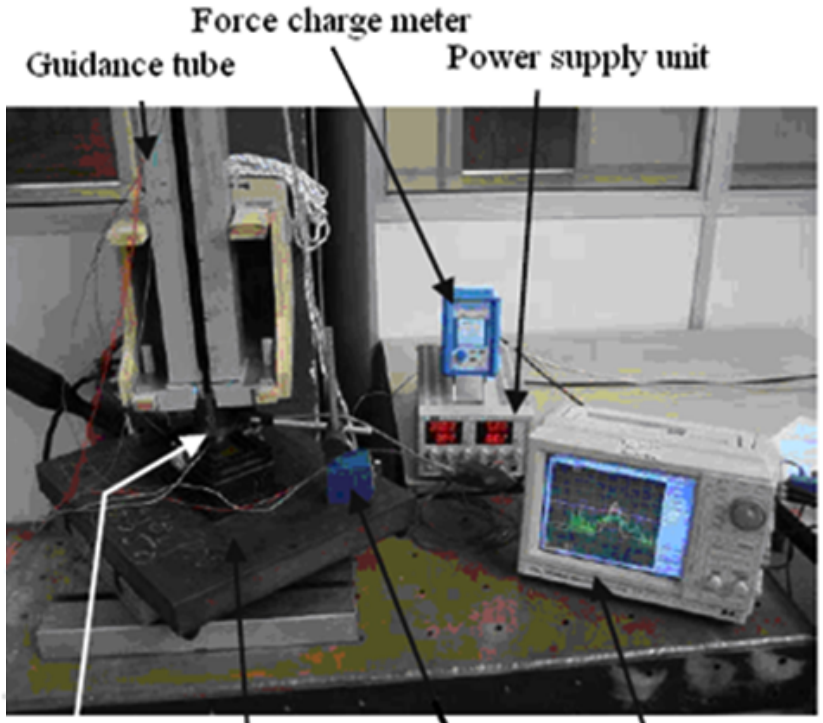
Vibration Test Results

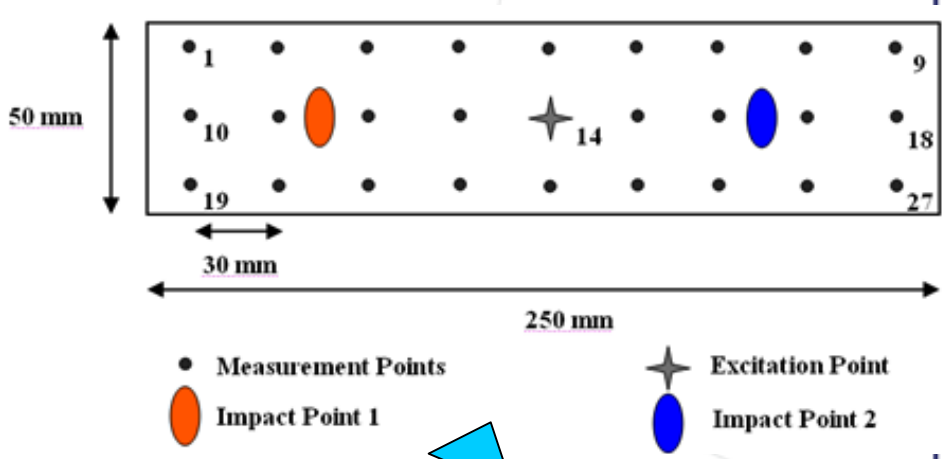


	Change in Damping Ratio	Change in Vibrational Level	Change in Weight
Entangled 10mm versus (Honeycomb, Foam)	+60 %	-16 dB	+96 %
Entangled 15mm versus (Honeycomb, Foam)	+215 %	-24 dB	+96 %
Entangled 15mm versus Entangled 10mm	+97 %	-8 dB	-

Monitoring of Impact Damage

Impacts Tests



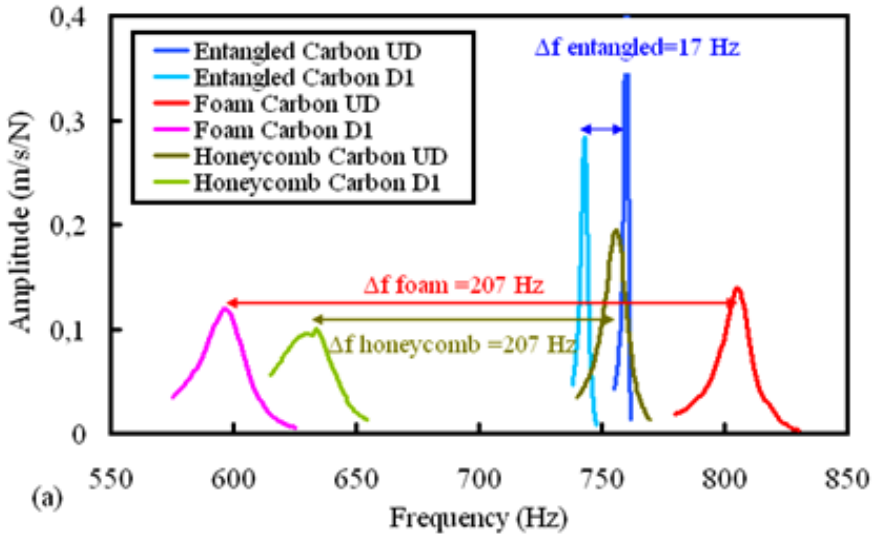


Two symmetric impacts have been carried out at each end

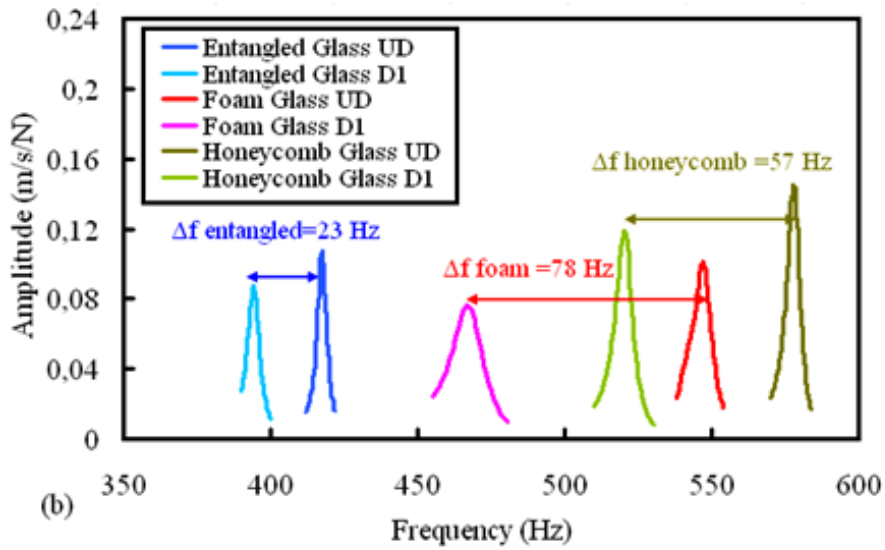
Barely Visible Impact Damage Limit (BVID) = 0.6 – 0.8 mm of indentation depth measured just after the impact

Evaluation de la résistance à l'impact par Pole Shifts

Carbon Beams



Glass Beams



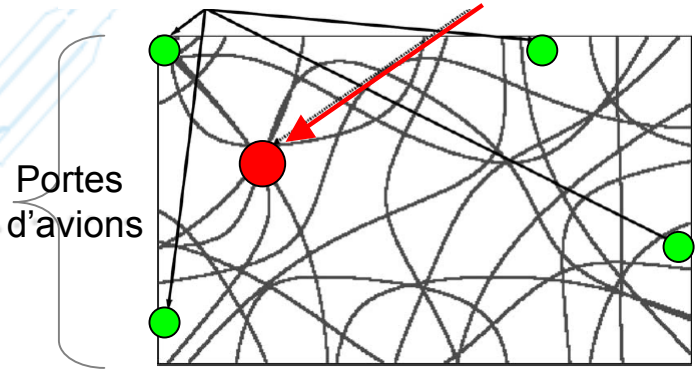
Conclusion of our Work

- 150 % higher damping ratios and 20 dB lower vibratory levels than the honeycomb and foam sandwich specimens, but are two times heavier.
- low static strength and should be used in specific applications where static strength is not the primary requirement
- Impacts are done below the BVID limit in order to detect damage by vibration testing that is hardly visible on the surface
- better impact toughness as compared to honeycomb and foam core sandwiches

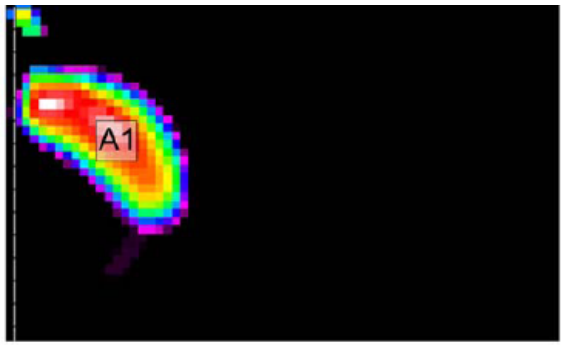
Projet EPICEA 2009

Intitule du projet : SAPES COMPOSITES
(Techniques innovantes pour le monitoring d'une structure de portes d'avion en composite par capteurs intégrés)
Partenaires : Medysys Air & Espace, Latecoere
Durée du projet : 24 mois
Objectifs: convaincre les avionneurs/constructeurs des limitations de l'inspection visuelle+ ultrasons
Couplage Ondes de Lamb Vibration ?

Piezo embarqués Impact



Localisation de la zone de l'impact: image des changements en fréquences, taux d'amortissements …

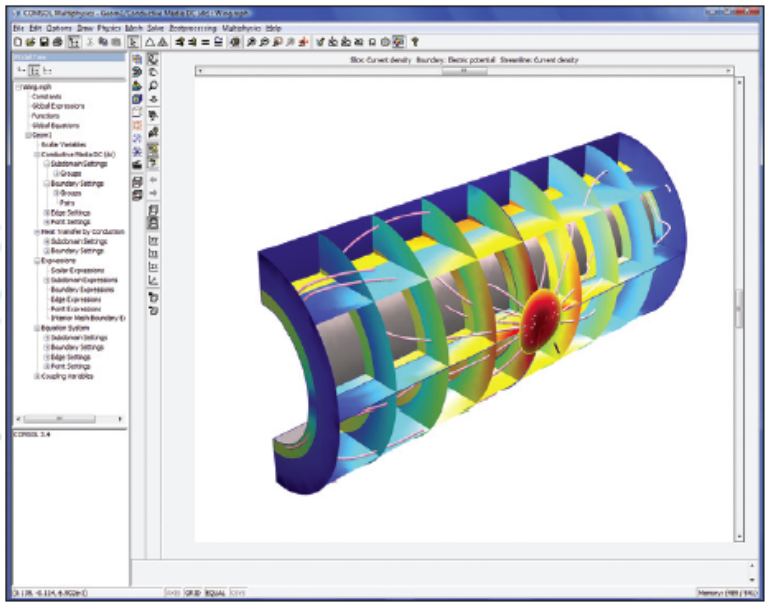


Méthodes de localisation par changement des caractéristiques modaux
Informations sur l'énergie d'impact ?

Lightning Strike



©U.S. Air Force photo/Senior Airman James Croxon



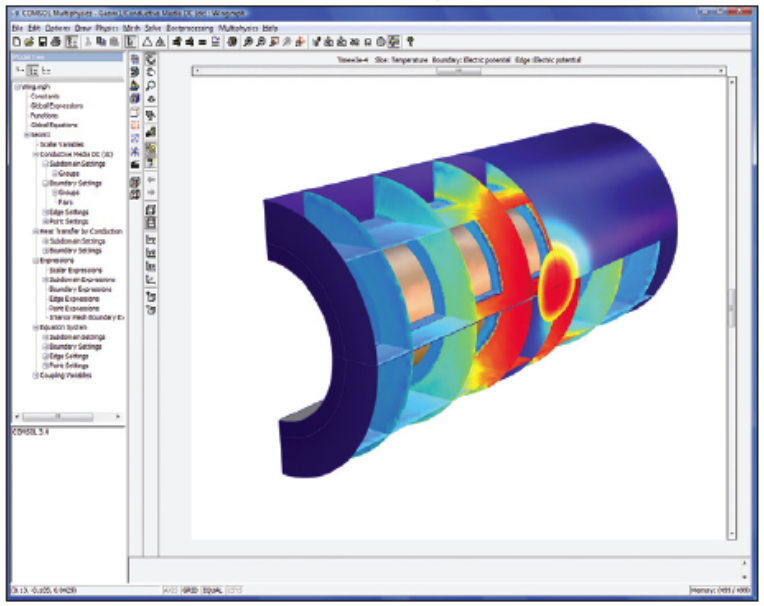
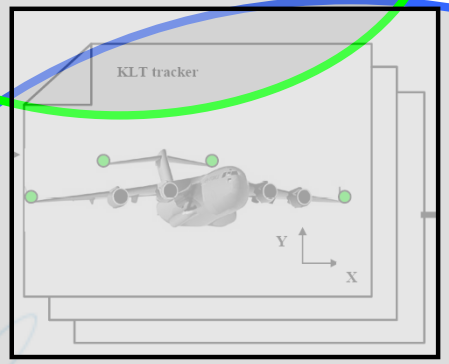


Figure 1: Model of lightning striking an airplane wing. On the left: the slice plot shows current density and the streamlines show current path. On the right: the slice plot shows the temperature, and the boundary plot shows the electric potential from the lightning strike.

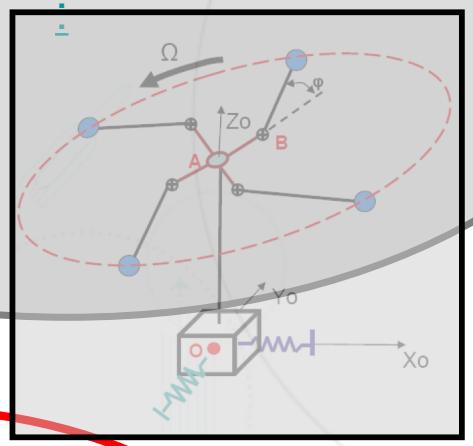
Intelligent sensors

Image processing
Embedded piezocomposites



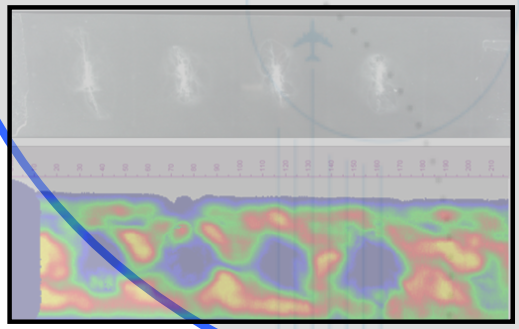
Nonlinear dynamics

GVT Rotor models and tests



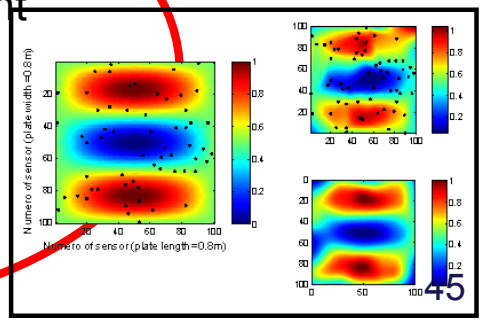
Structural Monitoring

Structural dynamics
FEM model update
Damage in composites



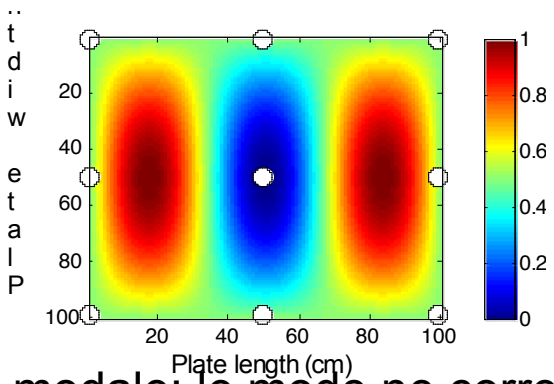
Signal processing, DOE

Optimal sensor placement
Transient Output only
Identification

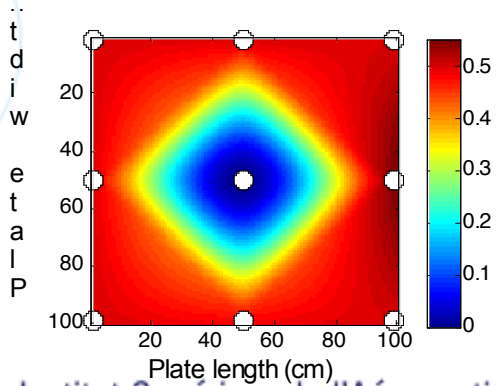


Placement optimal des capteurs

On veut par exemple obtenir le mode (2,1) avec 9 capteurs disponibles sur un panneau

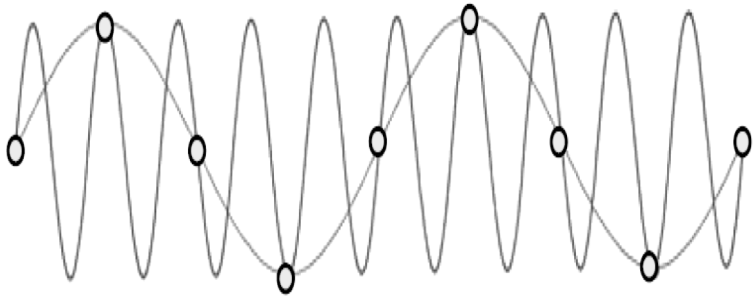


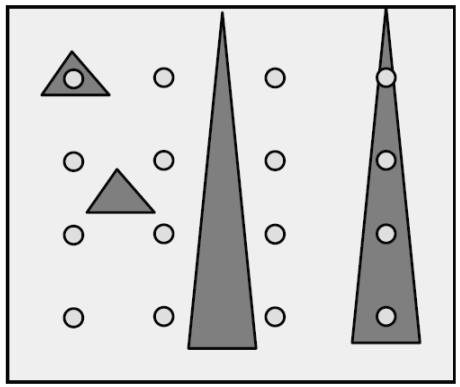
Resultats de l'analyse modale: le mode ne correspond pas a ce que l'on s'attend: repliement spatial → problème d'approximation et d'échantillonage



Repliement en 2D

Le “Mapping” consite reconstruire une fonction continue
à partir de valeur discrete (échantillonée)



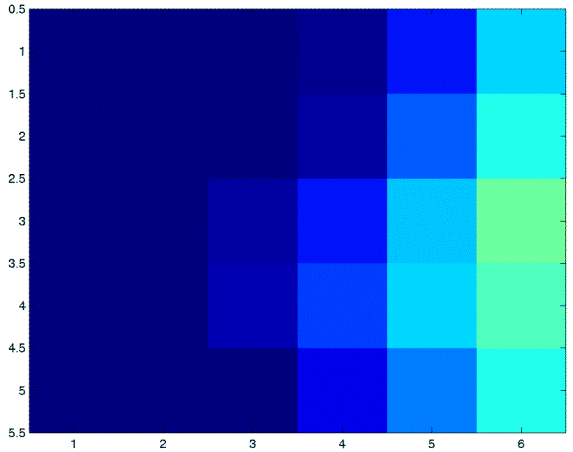


En général on constate des “artefacts” dû au sous échantillonage ou à l’utilisation d’une méthode d’approximation reconstruction peu fiable.:
Repliement temporel (Théorème de Shannon) (a), Repliement spatial (b)
dû à une résolution spatiale limitée qui induie une perte de détails

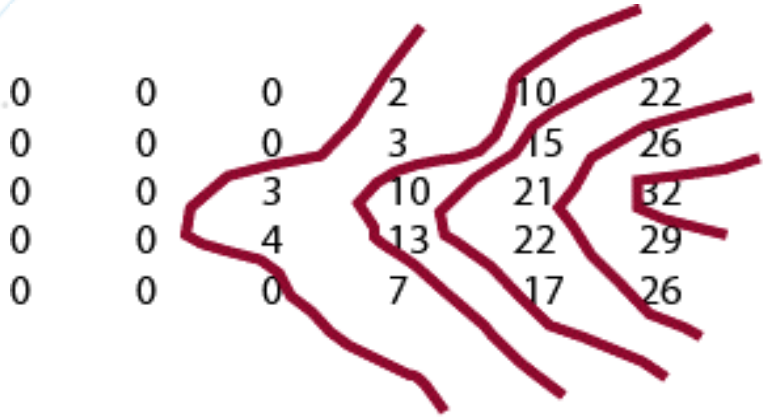
Exemple de mapping d'une matrice

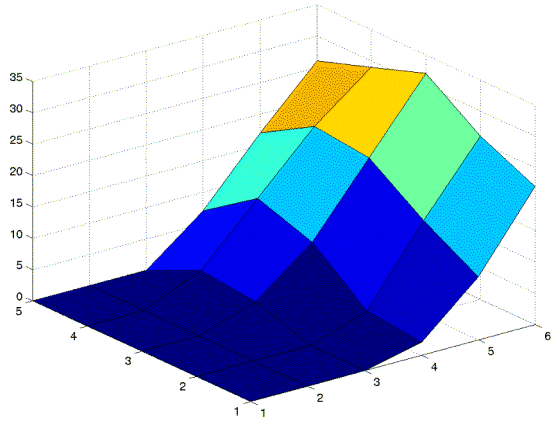
0	0	0	2	10	22
0	0	0	3	15	26
0	0	3	10	21	32
0	0	4	13	22	29
0	0	0	7	17	26

hand



Color shading

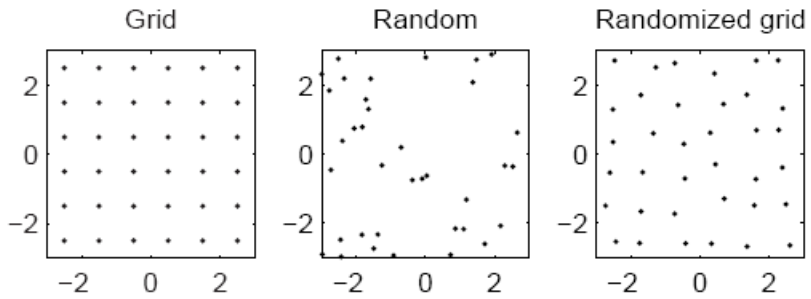


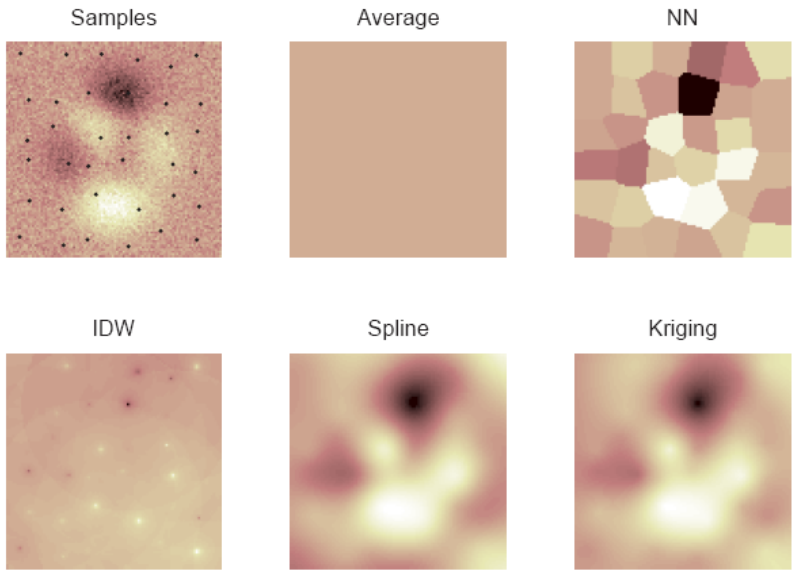


3D perspective

Méthode d'interpolation pour reconstruire une déformée 2D (surface)

On peut se demander ou placer les capteurs == comment échantillonner ?





Avec quelles méthodes ?
Quelle est la meilleure méthode ?
Surrogate models ?

2: *Results of using different interpolation methods for a given s*

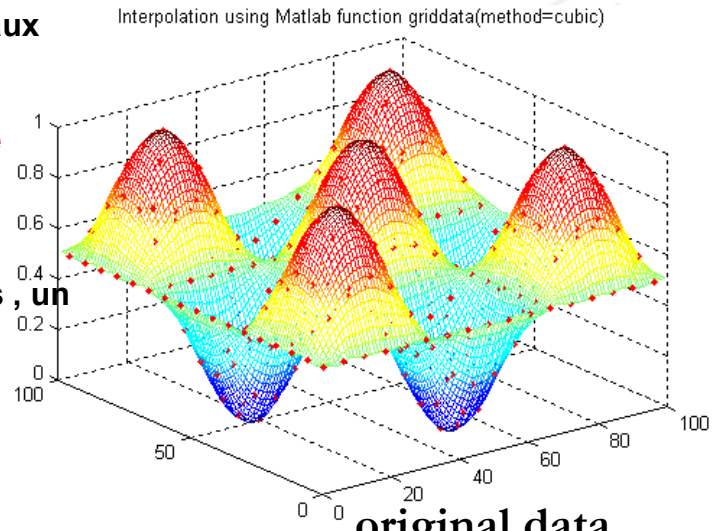
[25] Kirk K., Spatial sampling and interpolation methods - comparative experiments using simulated data, Master's thesis, Aalborg University, 2003.

Résultats IMAC 2009: Simulation numérique sur 14 modes en utilisant 2 méthodes simples d'interpolation : splines et kriging:

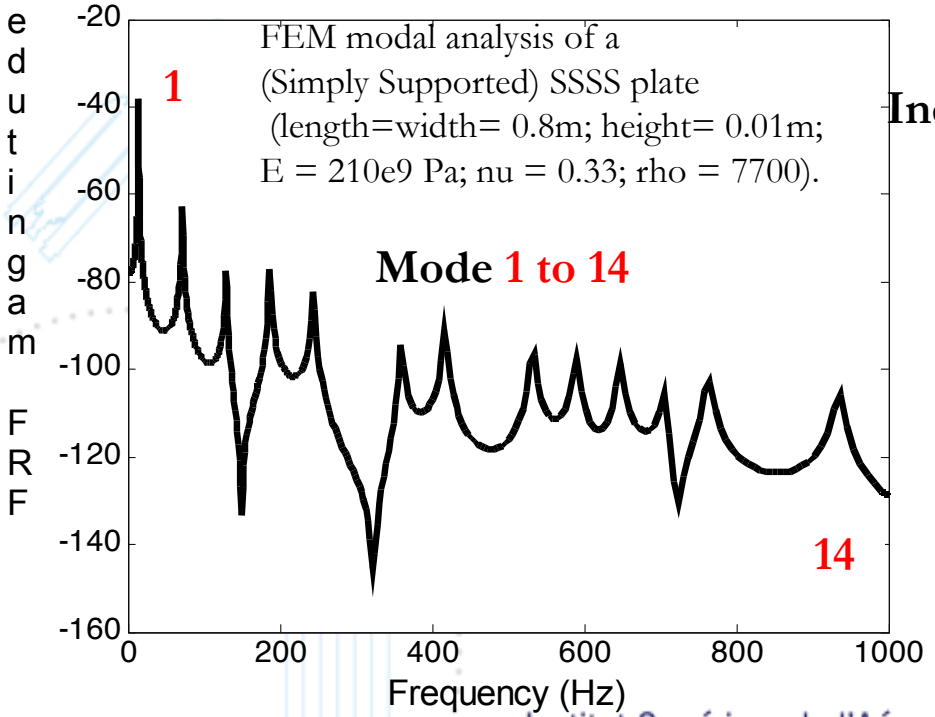
Qualité de la reconstruction est proportionnelle aux nombres de capteurs (grid or random)

--> Comment être sure de la reconstruction fidèle des 14 modes??

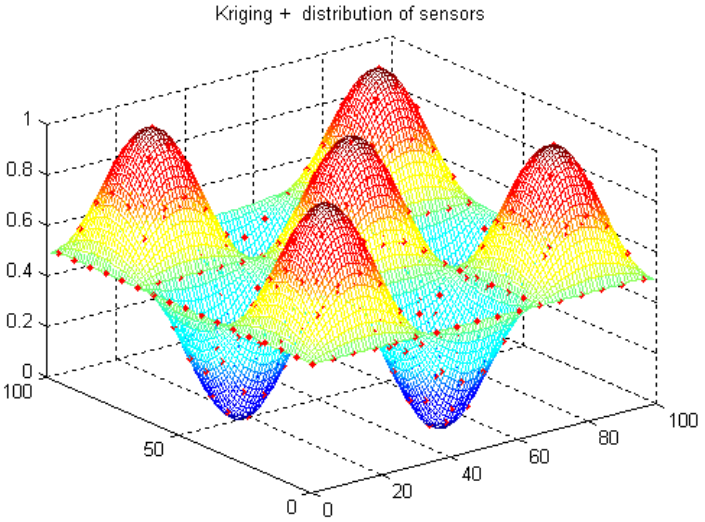
(le shift en fréquence augmente dans les hautes fréquences Là ou les capteurs sont moins fidéles , un défaut peut avoir plus ou moins d'influence sur certains modes seulement)



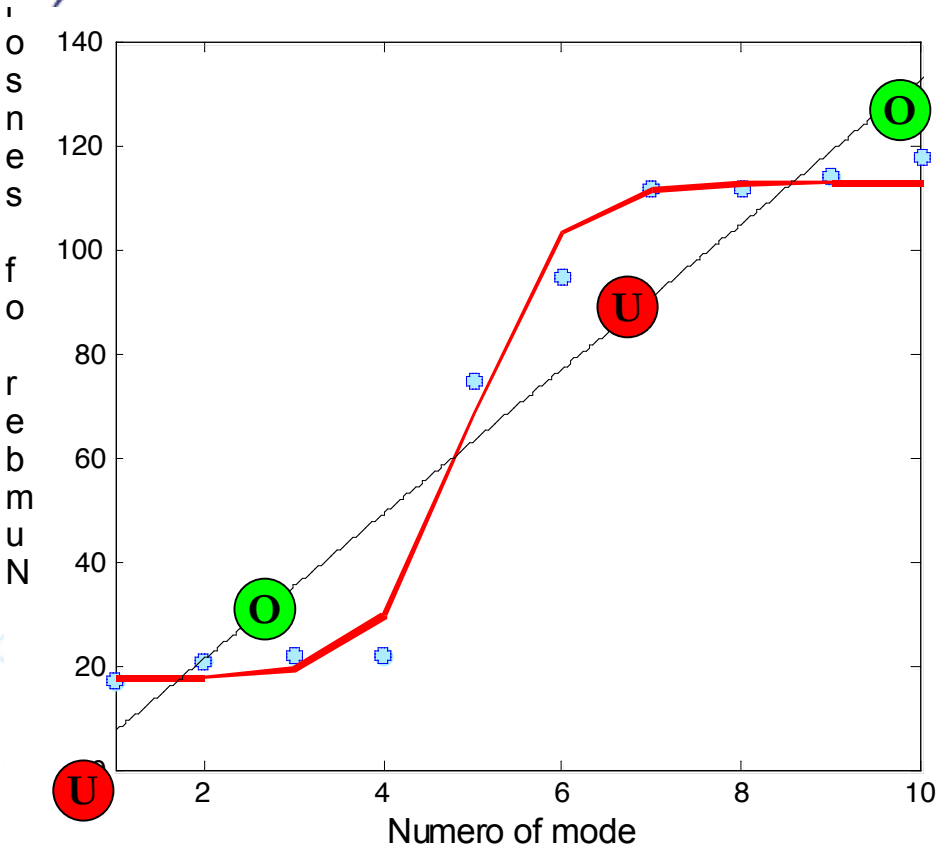
original data
100*100



Indicateur: RMSE



Corrélation entre les modes théoriques et les modes reconstruits



SSSS plate example:
10 modes in 0-700Hz

Les points bleus correspondent aux nombres
De capteurs nécessaires pour que la
La reconstruction ait un $R^2>0.95$
En ajustant une fonction sigmoide

$$Y = (max - min)/(1 + exp(-a - bX)) + min =$$
$$(95.35)/(1 + exp(4.93 - x)) + 17.73$$

O Oversampling

U Undersampling

$$y = 14x - 5.9$$

On voit qu'il est difficile meme sur un exemple simple de trouver le nombre optimal de capteurs (dans l'optique d'une détéction d'endommagment)

Résultats de la reconstruction est dépendant de la méthode d'intepolation (modèle réduit) → vers les ANN, MLS etc…plus robuste

Collaboration ENPC, HP Yin

For engineer one advantage of AIPR is the simplicity: every one knows the classical bandwidth method (Power ratio of 0.5). But here instead of determining the bandwidth for a given value of power ratio which requires numerical interpolations, the method involves an average inverse power ratio calculated at two frequencies symmetrically located from a peak. In this way, the damping estimation from a FRF becomes straightforward for simple modal test cases and would be sufficiently accurate provided that the coupling effects are not strong and the frequency resolution is high enough to determine accurately the peak amplitude frequencies.

average inverse power ratio (AIPR) method has been proposed in [16] for the damping estimation by using the following formula

$$\zeta = \frac{\omega^+ - \omega^-}{2\omega_{\max}\sqrt{\bar{\rho} - 1}}$$

Where $\bar{\rho}$ is an average inverse power ratio defined at two frequencies situated at the same distance δ from $\omega_{\max}$

$$\bar{\rho} = \frac{1}{2}\left[\frac{|H(\omega_{\max})|^2}{|H(\omega_{\max} - \delta)|^2} + \frac{|H(\omega_{\max})|^2}{|H(\omega_{\max} + \delta)|^2}\right]$$

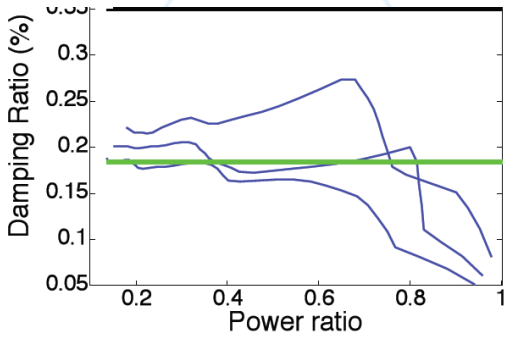


Figure 12: Damping estimation (undamaged case) using APR and RFP for 3 random points on 33 measurements points around 3rd bending mode (800 Hz). The red line is the average value for RFP (0.358%) and the green line is the average value for APR (0.183%) very close to LMS results.

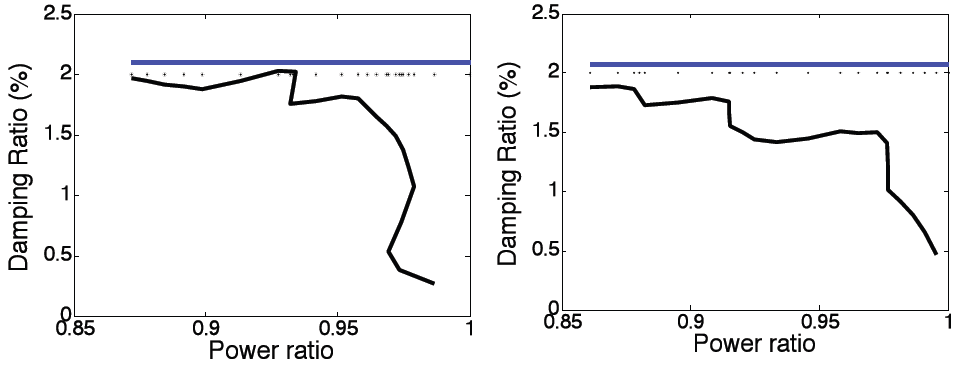
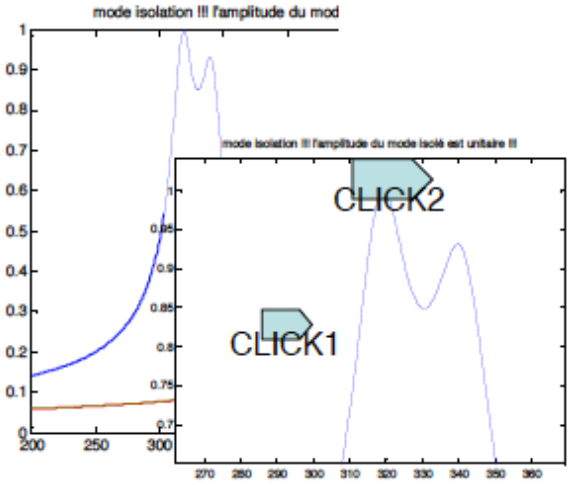
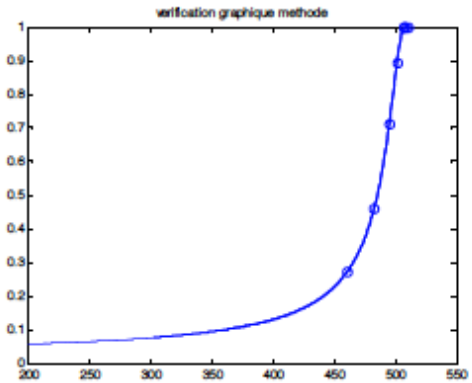


Figure 4: Damping estimation (2%) under different realization of a Gaussian noise process (SNR=30dB). RFP is able to fit the analytical model very well and so on limits the error in damping estimation whereas APR is underestimating the damping ratio.

IMPLÉMENTATION MATLAB





Trouve la fréquence de résonance fn (max dans la partie que tu isole entre deux clics de souris par exemple)

Interpole à une résolution de 0.25Hz (ou moins si tu veux de la précision …regarde cette effet)
Hi = interp1(f,H,fi,'linear');

Lance la méthode average power ratio (fonction qui calcule: Beta,f+, f-, fn,e t qui renvoi etha_identifié en fonction de alpha)

1ˣ Valide sur les exemples de Yin (en isolant les 3 pics, 3 valeurs de résolution, 3 etha)

2ˣ Teste 3 amortissements très différents (petit, moyen, grand) et un terme nonlinéaire ?

3ˣ Teste 3 Valeurs de SNR

4ˣ Conclure, Sachant que l'on a pas mis en place l'outil d'isolation des modes

Substraction technique and finite difference formulas for modal parameter estimation
***Mechanical Systems and Signal Processing**, Volume 18, Issue 6, November 2004, Pages 1497-1503*
H. P. **Yin**, D. Duhamel

Comparaison statistique d'estimateur d'amortissement

Previous works have demonstrated the ability of RFP method to distinguish resonance even at high noise level **[26]** among these methods:

The Complex-Exponential Method
The Hilbert-Envelope Method
The Ibrahim Time Domain method

The CWT method highlights better results in some minor cases: lower damping ratio corrupted with noise, separate modes **[27]**

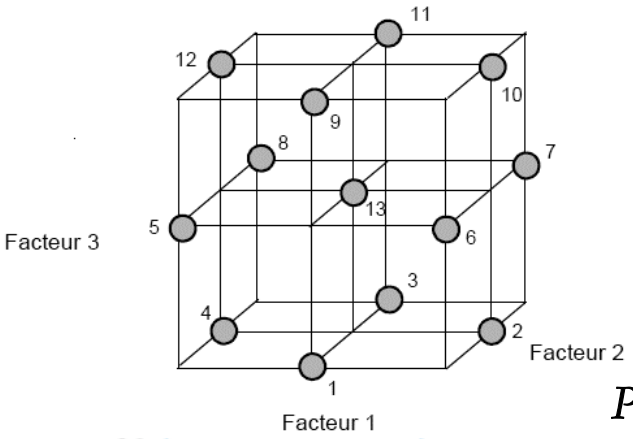
Which method do we use for a SHM purpose ?

Solution: a more detailed supervised Benchmark !

[26] Iglesias A.M., Investigating Various Modal Analysis – Extracting Techniques to Estimate Damping Ratio, Master of Engineering, Virginia Polytechnic Institute, 2000.
[27] Wu J.Y., Extracting Damping Ratio Using Wavelets, Master of Engineering, Massachusetts Institute of Technology, 2001.

Plan d'expériences

A study of sensitivity is presented in order to deduce the significant factors.
This study is carried out on simulated FRF with the aim of identifying the factors which have the most significant effect on the three damping estimation algorithms.



Frequency Resolution FR,
Signal to Noise Ratio SNR,
Damping Ratio Level DRL

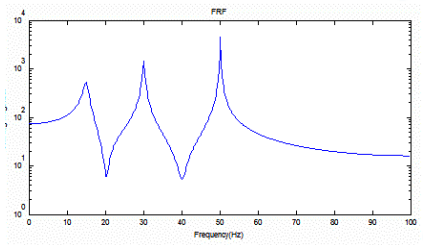
$$P\_RFP = +0.3 + 0.4FR + 1.5SNR + 0.5DRL$$

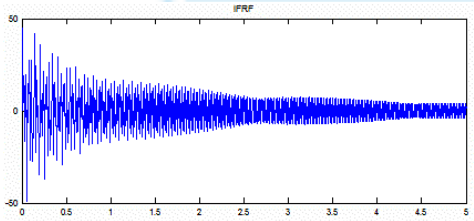
INTERACTIONS

$$+ 0.7FR.SNR - 0FR.DRL$$
$$+ 0.8SNR.DRL + 0FR^2 + 1.2SNR^2 + 0DRL^2$$

The full factorial DOE requires 81 experiments as Box-Behnken design reduces the computational time into 27 experiments and the quality of the information you get will be higher.

Paramètres





Step1: Signals simulation (IRF, FRF) of known properties

Frequency Resolution FR, Signal to Noise Ratio SNR, Damping Ratio Level DRL

Step2: Damping estimation using the 3 algorithms, computation of the errors

Step3: Compute the sensitivity of the estimation function of these parameters

Step4: Repeat the previous step with influence of the last parameter **Modal Density MD**

Step5: Compare the results (importance of the MD in the damping estimation)

First DOE

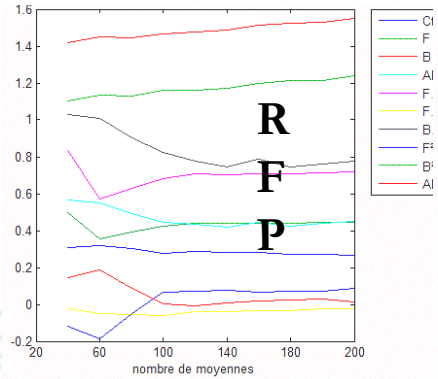
Level	***Low***	***Middle***	***High***
Signal to Noise Ratio (*SNR*)	80dB	40dB	20dB
Frequency resolution (*FR*)	0.2Hz	0.5Hz	1Hz
Damping Ratio Level (*DRL*)	0.1%	0.7%	4%
Modal D ensity (*MD*)	3 modes/35Hz	3 modes/15Hz	3 modes/7Hz

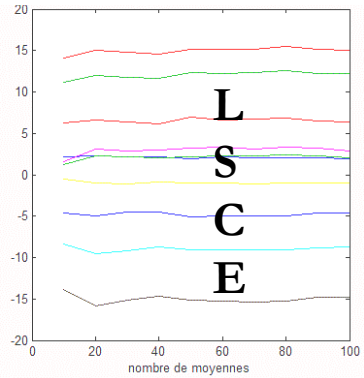
2nd DOE

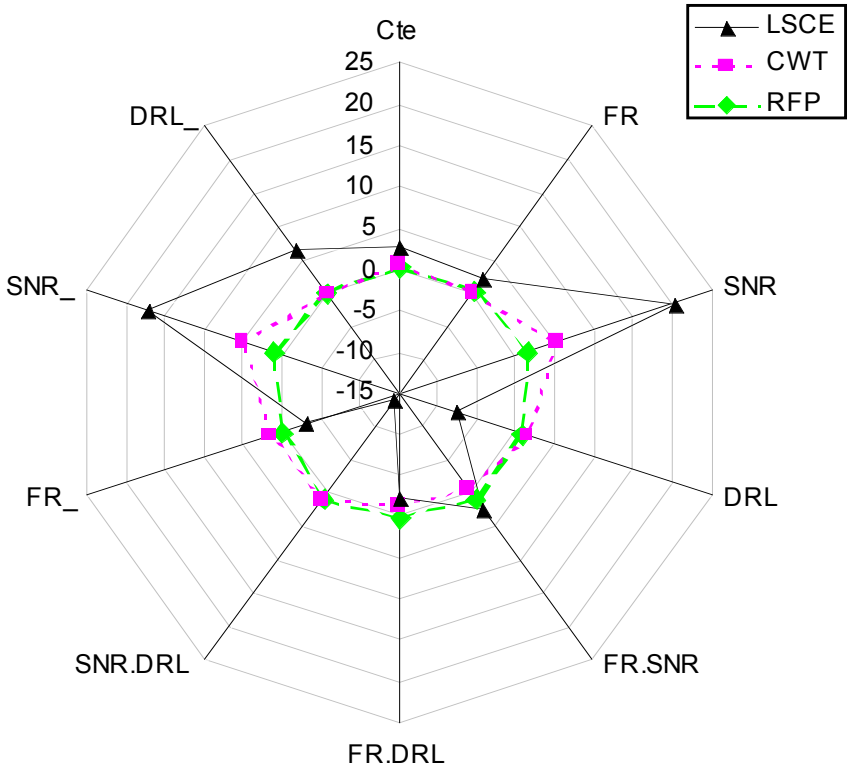
Approche Monte Carlo

we have synthesised one noisy FRF by experiment and the white noise is recomputed at each iteration of the Monte Carlo simulation (100 steps).

This mixed approach permits to study not only the accuracy of the identification algorithm but also the robustness

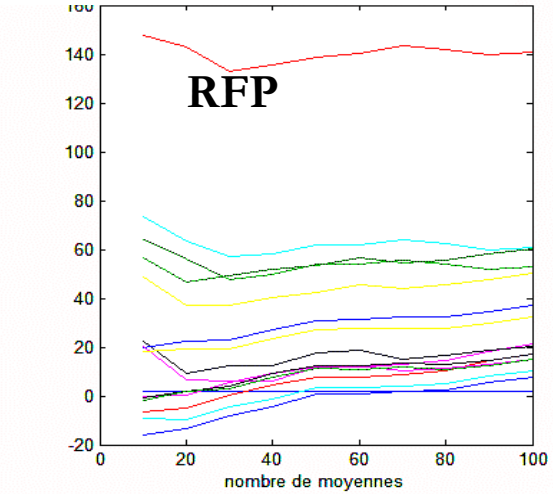


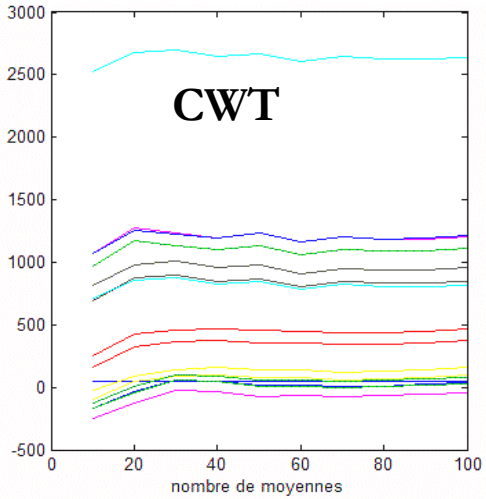


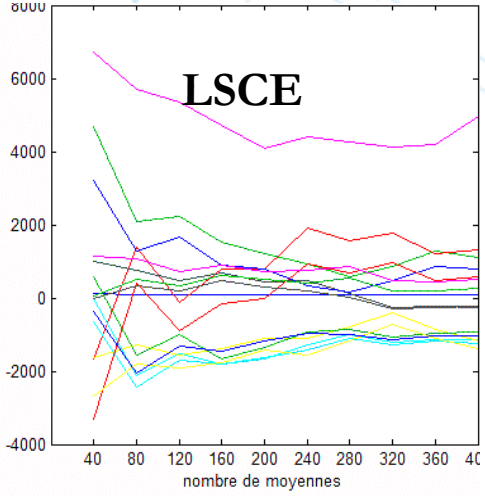


After 100 iterations the coefficients converge (the weight of the effects are stable).

Paramètres influents ?



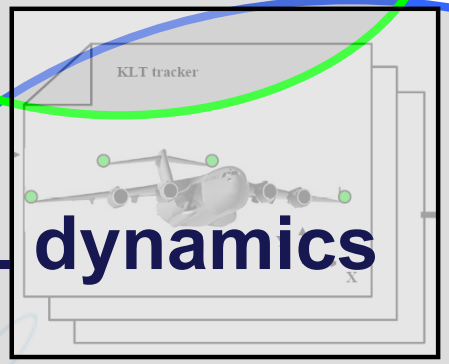




	RFP	CWT	LSCE		RFP	CWT	LSCE
Cte	2	50,9	84,5	F^R . SNR	43,8	58,7	-1171,7
FR	54,3	1097	1112,2	F^R . MD	16,4	834,9	-279,2
SNR	140,4	430,1	1333,1	F^R . DRL	29	1193,2	797,1
MD	62,3	2634,9	-1155,7	SNR . MD	53,9	44,4	-940,1
DRL	10,5	1194,5	4970,3	SNR . DRL	5,8	335	587

Intelligent sensors

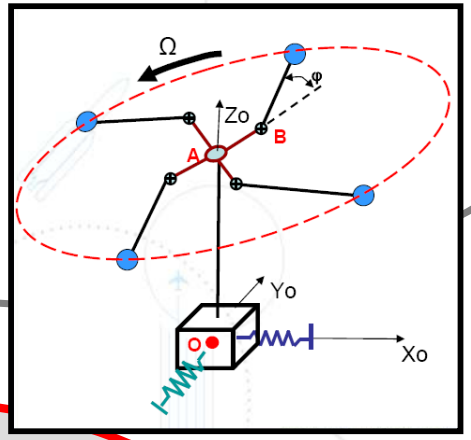
Image processing
Embedded piezocomposites



NL dynamics

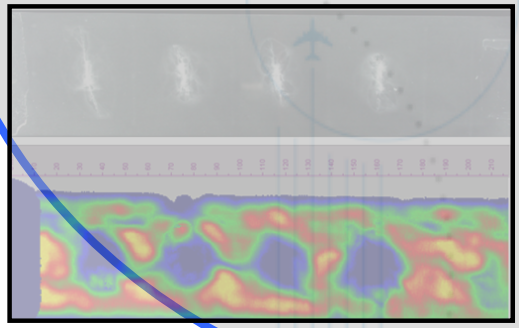
Nonlinear dynamics

GVT Rotor models and tests



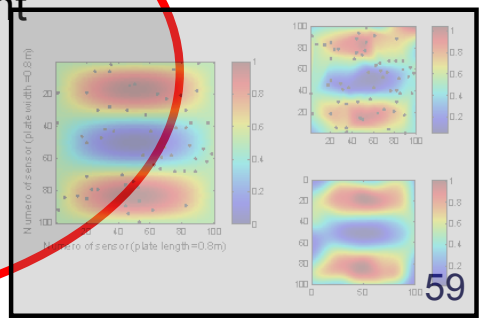
Structural Monitoring

Structural dynamics
FEM model update
Damage in composites



Signal processing, DOE

Optimal sensor placement
Transient Output only
Identification



Contexte thèse INRIA ISAE

Phénomène Résonance Sol :

- Instabilité dynamique spécifique aux hélicoptères
- Destruction total de l'appareil

- Vérifier les principales conséquences dans la prédiction de la zone d'instabilité provenant de l'existence du caractère périodique dans les équations





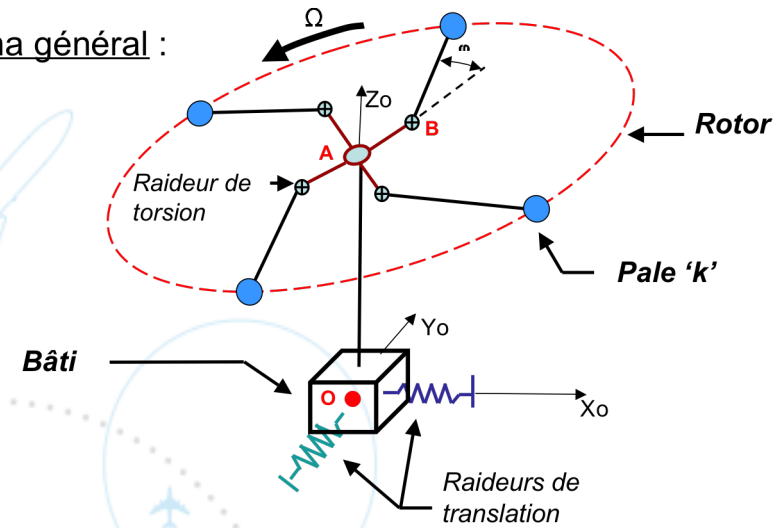
CH-47 – Chinook soumis à test de résonance sol

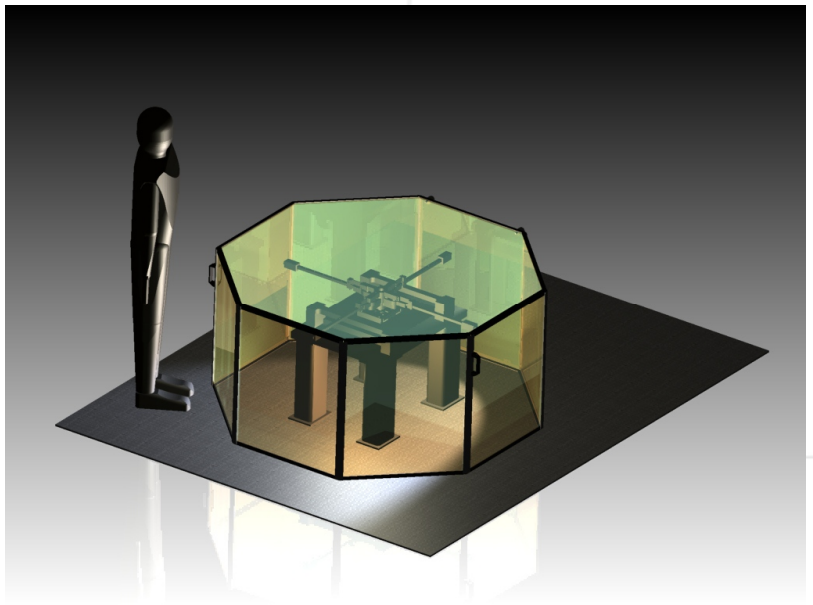
(www.youtube.com)

Banc numérique et « analogique »

- Collaboration entre les thésards

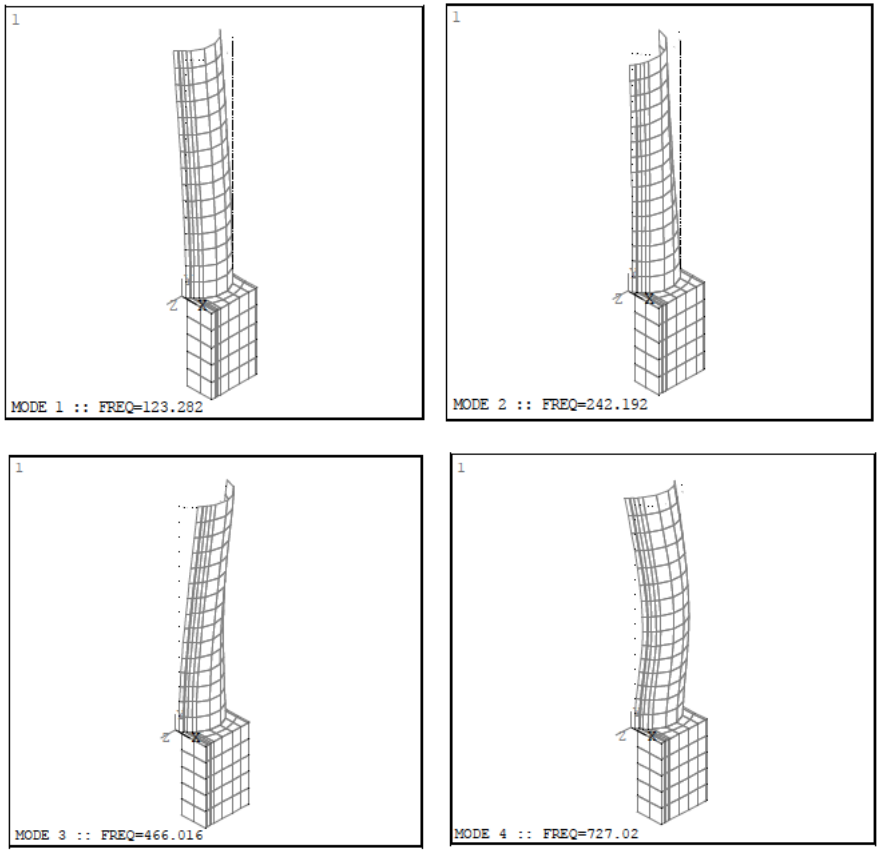
- Schéma général :



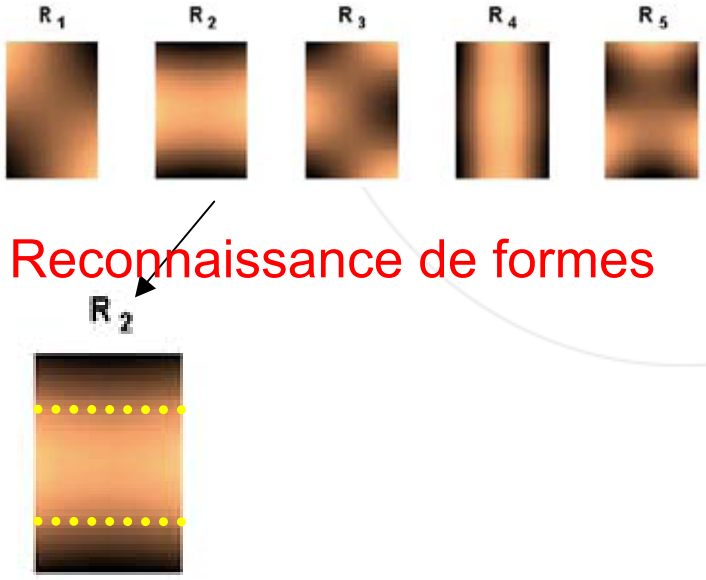


PROJET ISAE/INRIA

- Reconnaissance intelligente de déformées modales: application aux aubes de turbines
- M. Bergh ITA brésil (6 mois)

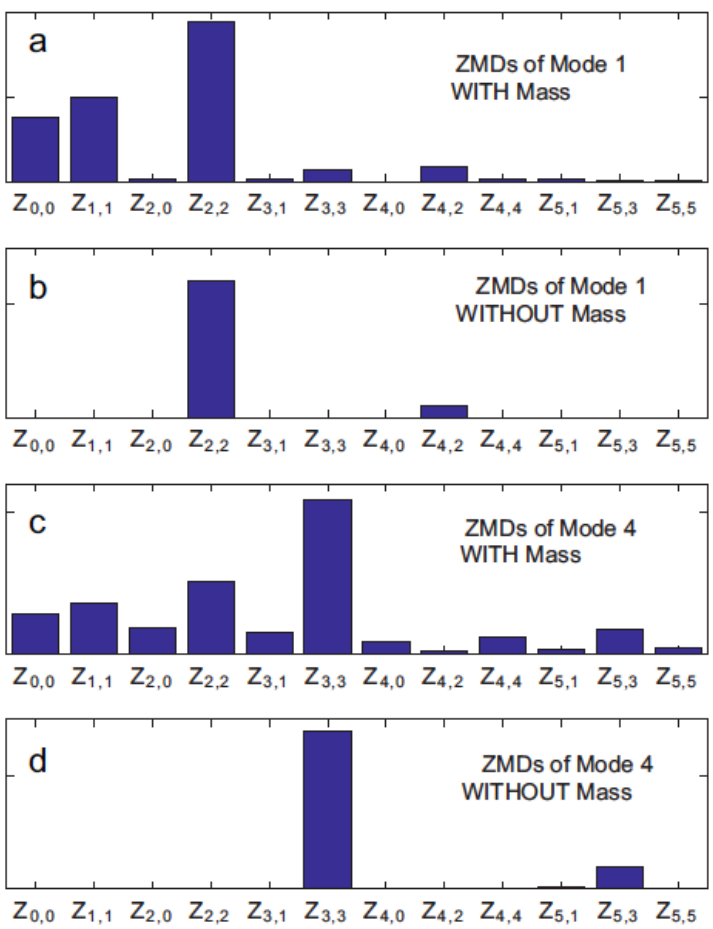


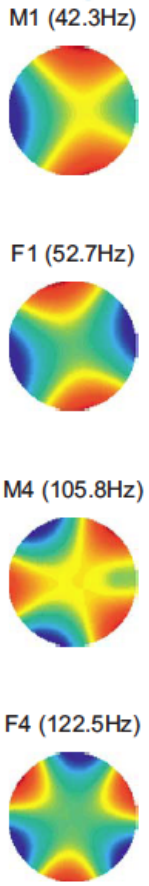
Mapping



Descripteurs de déformée: Zernike Descriptor

F. Zernike, *Physica,* 1 (1934), 689.





MAC Vs ZMD

- Victor WANG Dynamics & Control University of Liverpool
- --> Collaboration sur toolbox Matlab

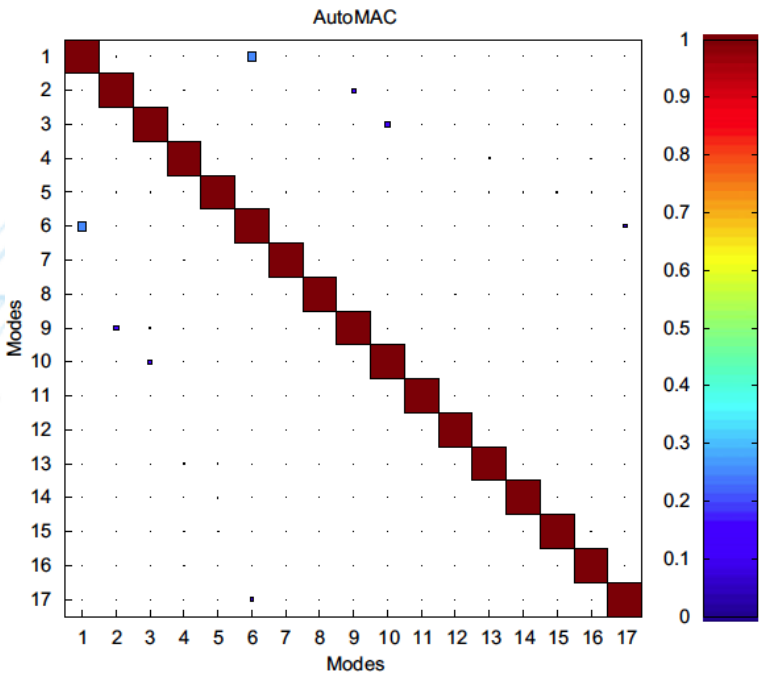


Fig. 21. AutoMAC for the disc-elastic foundation model.

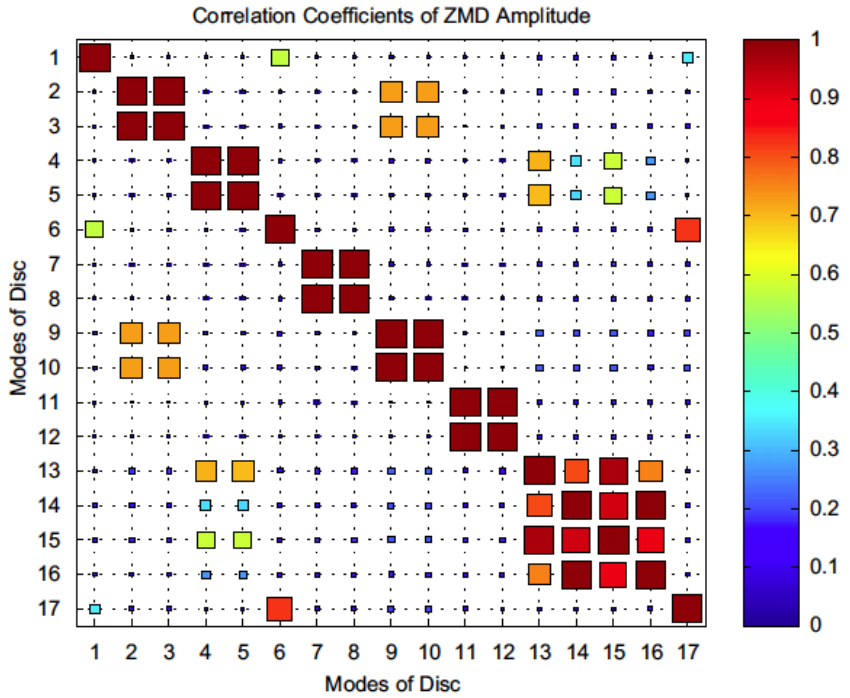


Fig. 22. Autocorrelation of ZMD amplitudes.