Projet FUI SICODYN

01 janvier 2012- 30 avril 2016

pour des SImulations crédibles via la COrrélation calcul-essai et l'estimation d'incertitudes en DYNamique des structures

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Durée du projet	52 mois
Coût du projet	3,82 M€
Aide BPI	1,45 M€
Aide FEDER	68,9 k€
Labellisation	Pôle SYSTEMATIC Pôle Nucléaire Bourgogne Pôle des Microtechniques
Pilotage	EDF R&D

Sommaire

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Les 13 partenaires

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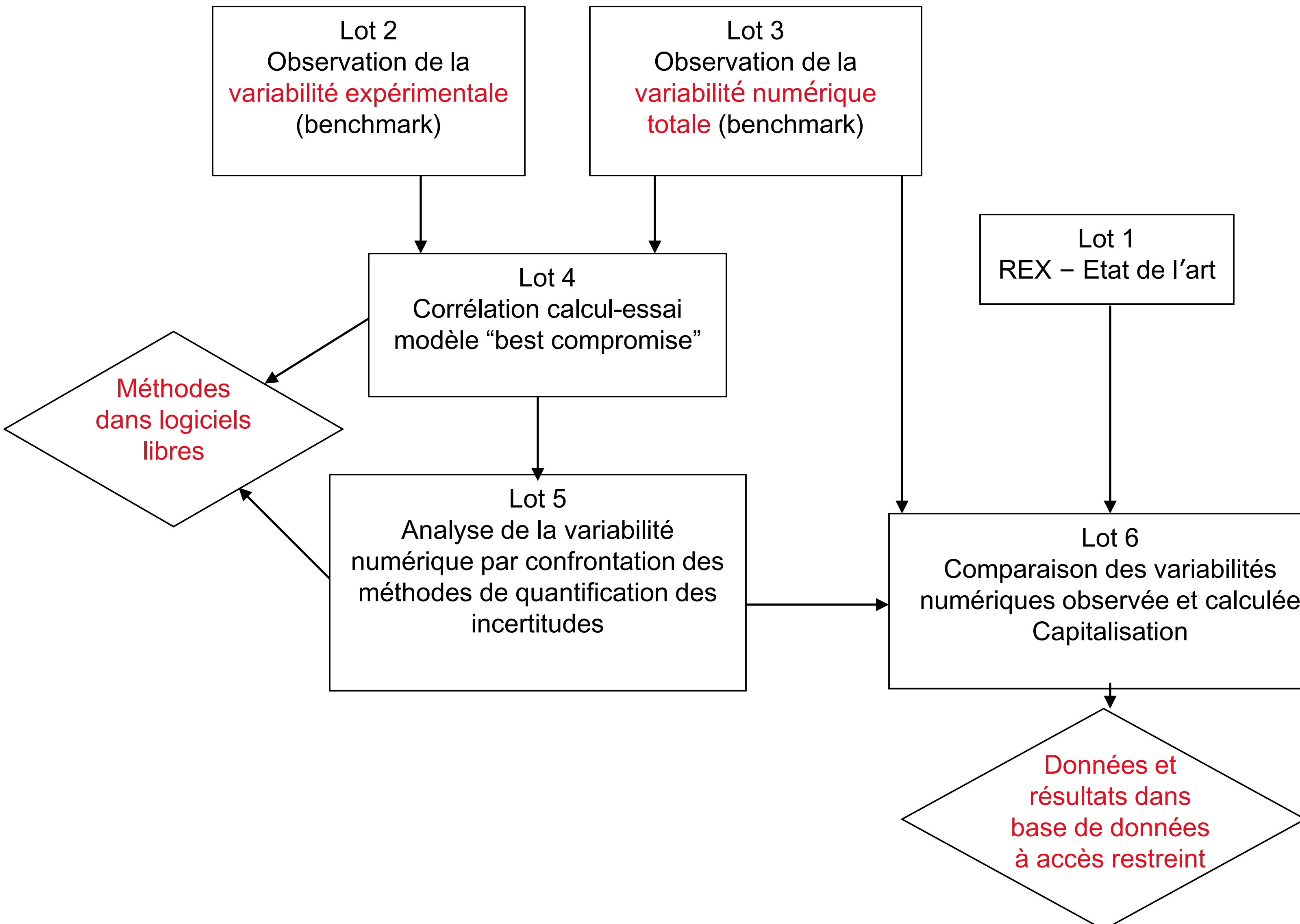
Grands groupes	AIRBUS Defence & Space	EDF	NECS	SULZER Pompes France
Etablissements de recherche	CETIM			
Moyennes entreprises (entre 250 et 2000 personnes)	SAMTECH	SOPEMEA		
PME (<250 personnes, définition européenne)	PHIMECA Engineering	VIBRATEC		
Académiques	ENS Cachan	FEMTO-ST	INSA Lyon	MSME

Contributeurs EDF R&D : AMA, MRI, MFEE

Structuration scientifique



Structuration scientifique (autre présentation)

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- 1. Les benchmarks →
  - Lot 2 : observation de la variabilité numérique
  - Lot 3 : observation de la variabilité expérimentale
- 2. Les méthodes →
  - Lot 1 : état de l'art
  - Lot 4 : corrélation calcul-essai
  - Lot 5 : estimation des incertitudes
- 3. La capitalisation →
  - Lot 6 : versement dans logiciels libres et base de données

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Scientific innovations

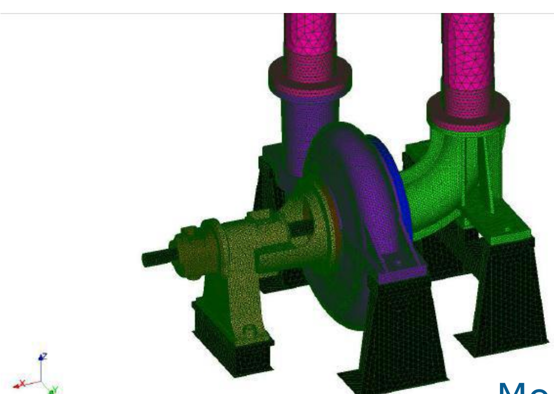
1. Illustration of the complete procedure 1) modeling at macro-level, 2) a priori estimation of uncertainties, 3) measurement, 4) test-analysis correlation
2. Application of methods tested on academic examples on a complex structure in industrial environment
3. Observation of the experimental variability on an in situ industrial system (benchmarks)
4. Observation of the total numerical variability by reproducing the real conditions of a study conducted by a design office (benchmarks)
5. Development and application of methods to quantify the total numerical uncertainty (parametrical + model form uncertainty)
6. Evaluation of the capacity of methods to quantify the total numerical uncertainty by comparison with the observed variability thanks to benchmarking operations

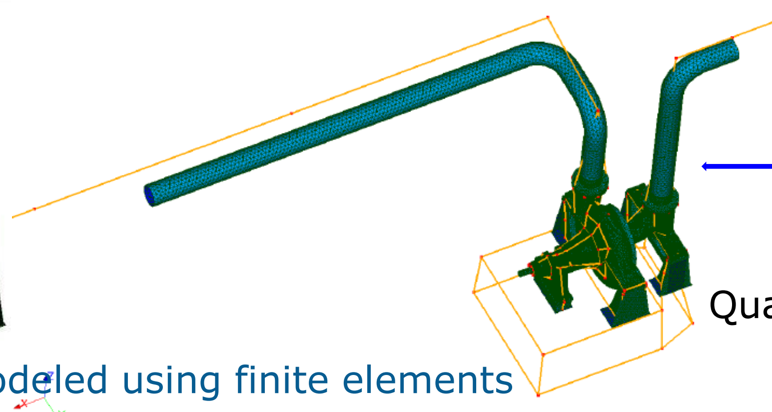
Main demonstrator: Booster pump in industrial environment in EDF thermical plant

The Booster pump in SULZER Pumps France factory

The in situ non connected pump

In situ



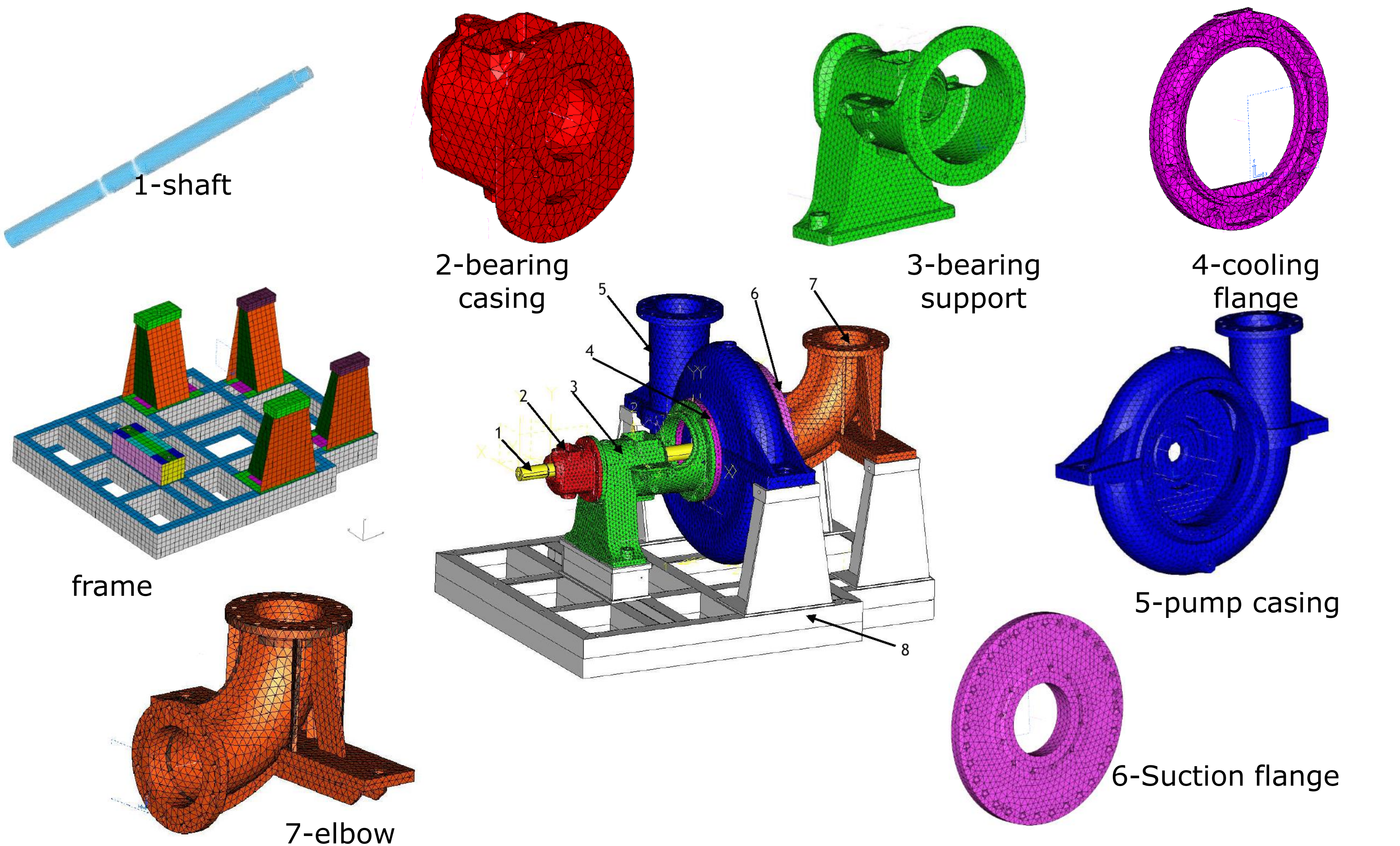


The pump connected to delivery and pipes

Quantity of interest: eigenmodes

Modeled using finite elements

The 8 main pump components



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Observation de la variabilité numérique
Confrontation calculs-essais

1. Structure de laboratoire (bibliographie)
2. Composants industriels libre-libre
3. Structure assemblée industielle

Méthode : 7 équipes indépendantes réalisent les mêmes calculs modaux

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Bibliographie benchmarks en dynamique des structures
Exemple

Quantification of prediction bounds caused by model-form uncertainty

Report LA-UR-13-27561, L.M. Gonzales, T.M. Hall, K. Van Buren, S. Anton, F.M. Hemez, 27 september 2013

K. Van Buren, T.M. Hall, L.M. Gonzales, F.M. Hemez, S. Anton, A case study to quantify prediction bounds caused by model-form uncertainty of a portal frame, Mechanical Systems and Signal Processing 50-51 (2015) 11-26

1st configuration: the built-up system with complex boundary conditions

3-component frame, bolted assembly:

- 2 vertical columns
- 1 top, horizontal beam

frame bolted to a base plate

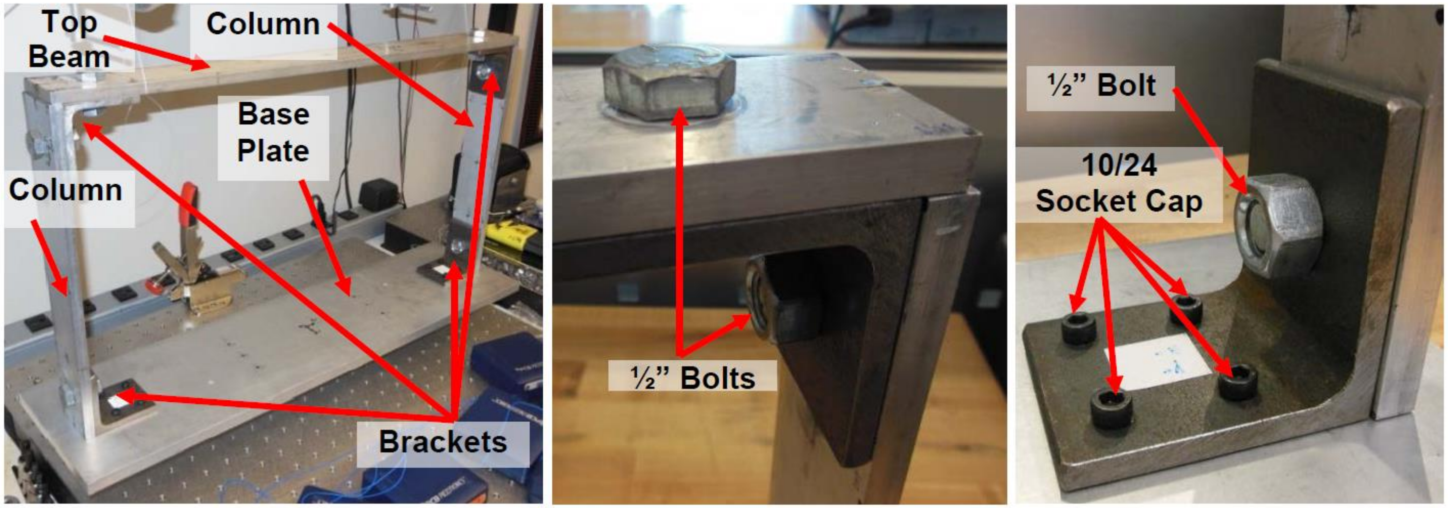


Figure 1: Portal frame (left), top-side bolted joint (middle) and bottom of the frame (right).

Predict with accuracy the dynamic behaviour of the portal frame (4 first eigenmodes)

Methodology applied: 7 independent groups of students

Experimental

7 different frames fabricated, based on the same design specifications ➔ measure unit-to-unit variability

Disassemble and reassemble the structure between experimental tests ➔ test-to-test variability

Different tasks for each test: data acquisition, impact hammer, analysis of data

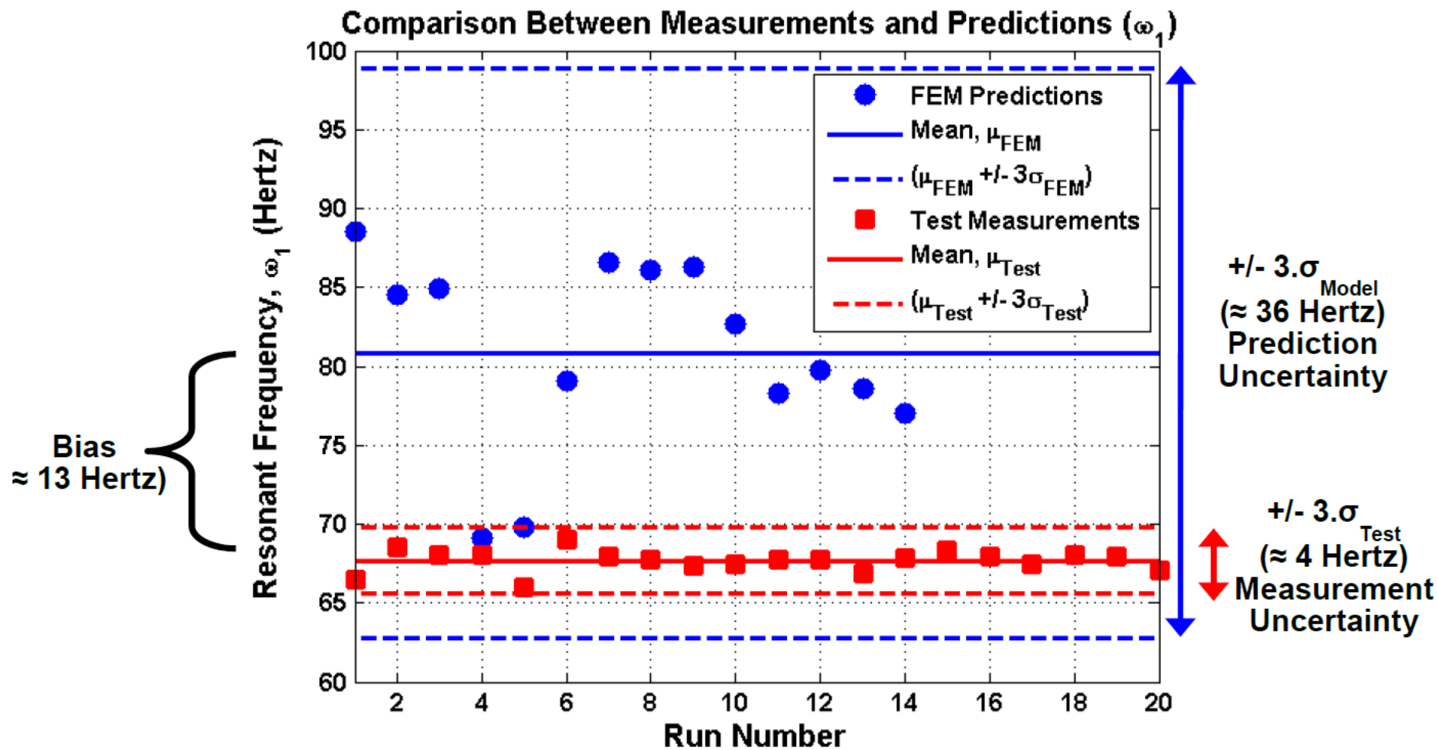
Numerical

Each group develops 3 numerical FE models
- Beam (1D)
- Shell (2D)
- Continuum (3D)

Material properties (steel, aluminium) imposed

Bolted connections all represented by coincident nodes

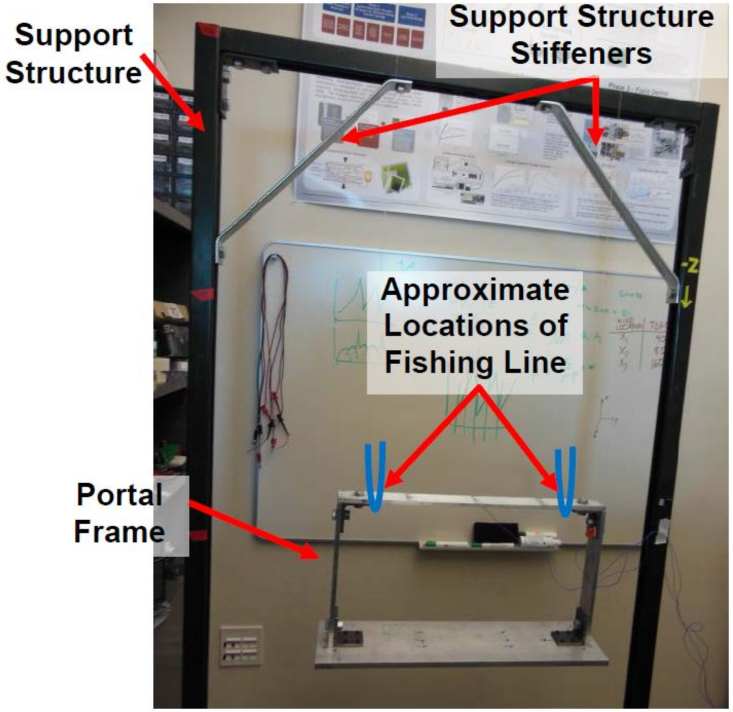
Variability of the first frame eigenfrequency

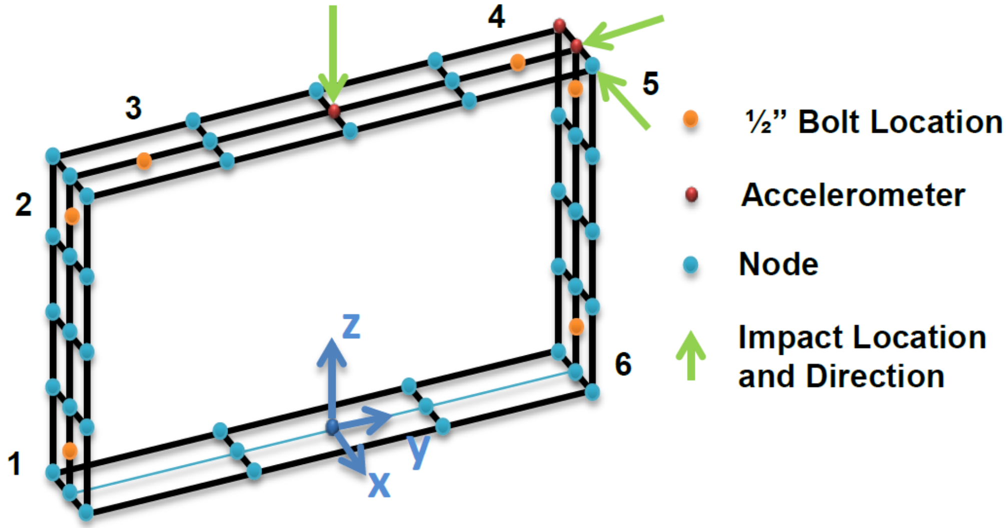


Main contribution of the prediction bias: boundary condition

➔ free-free boundary condition imposed for work presented hereafter

2nd configuration: the free-free built-up system

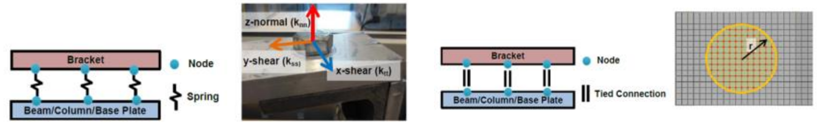




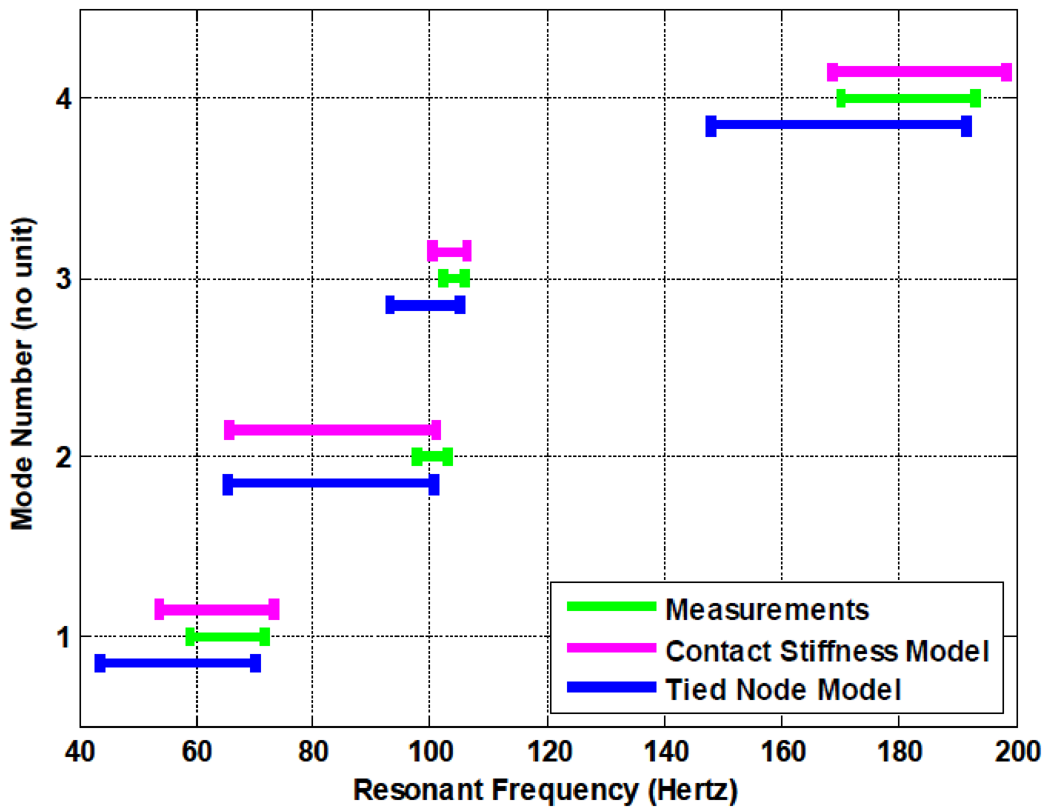
Experimental configuration and instrumentation setup

Lot 1

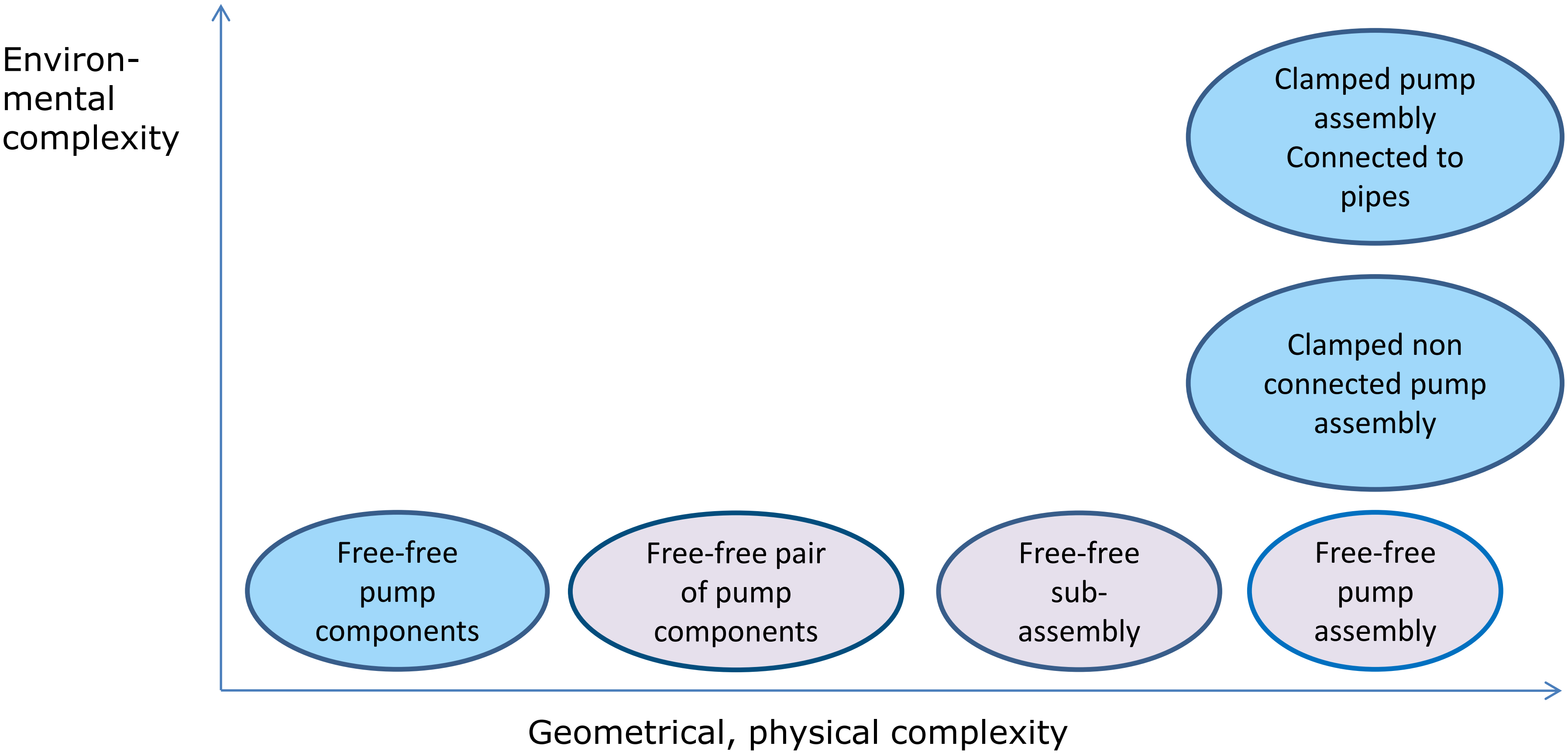
Test-analysis correlation of the portal frame structure



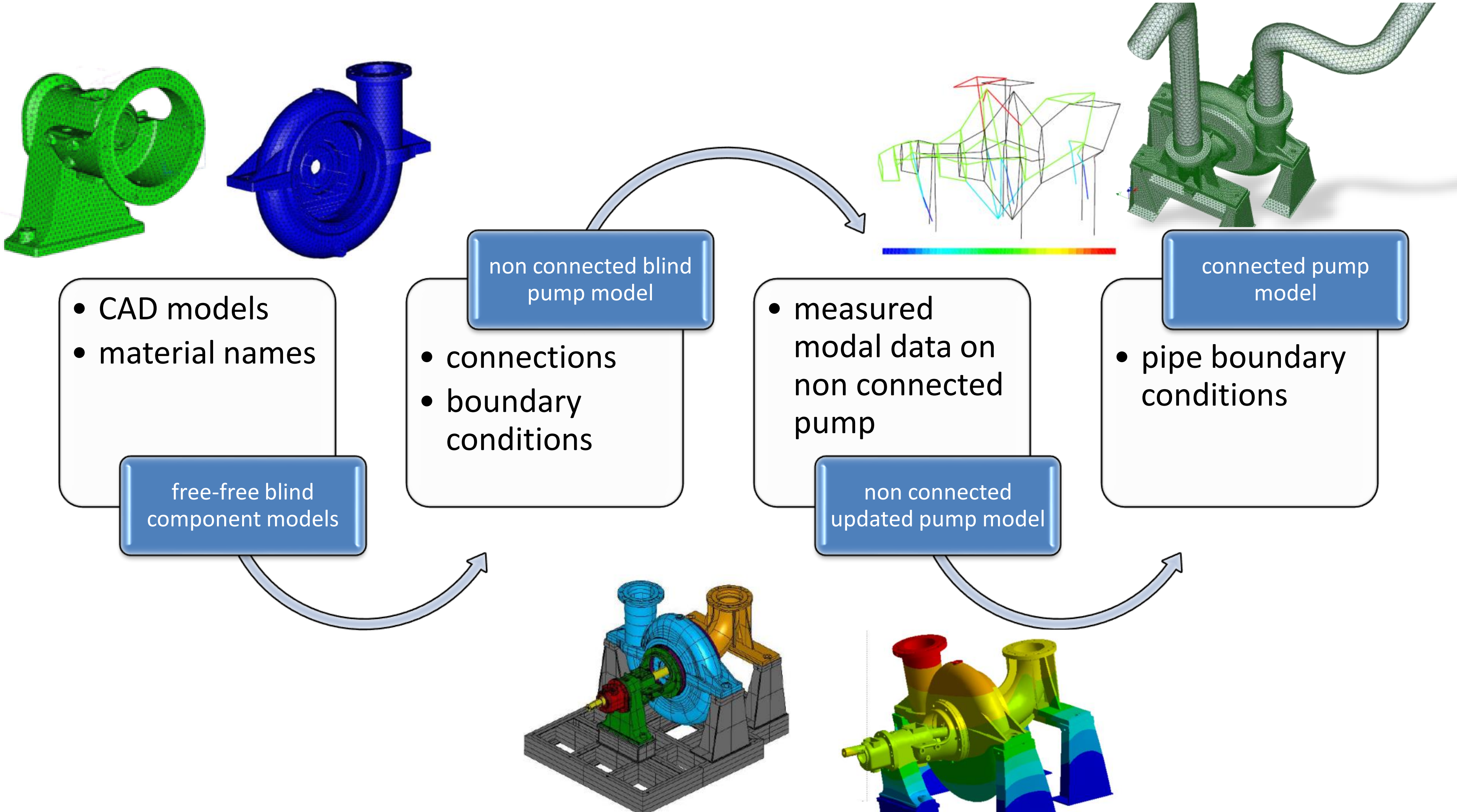
Resonant Mode	Measurements		Contact Stiffness Model		Tied Node Model	
	Bounds (Hertz)	Range (Hertz)	Bounds (Hertz)	Range (Hertz)	Bounds (Hertz)	Range (Hertz)
1	58.8-to-71.6	12.8	53.8-to-73.1	19.3	43.5-to-70.4	26.9
2	97.5-to-103.0	5.5	65.8-to-101.2	35.4	65.5-to-100.5	35.0
3	102.0-to-106.0	4.0	100.4-to-106.2	5.8	93.2-to-105.3	12.1
4	170.0-to-193.0	23.0	168.5-to-198.3	29.8	148.0-to-191.7	43.7



Une démarche progressive

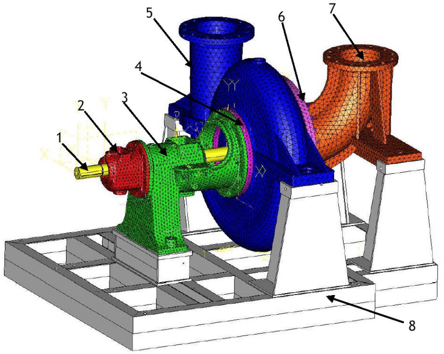


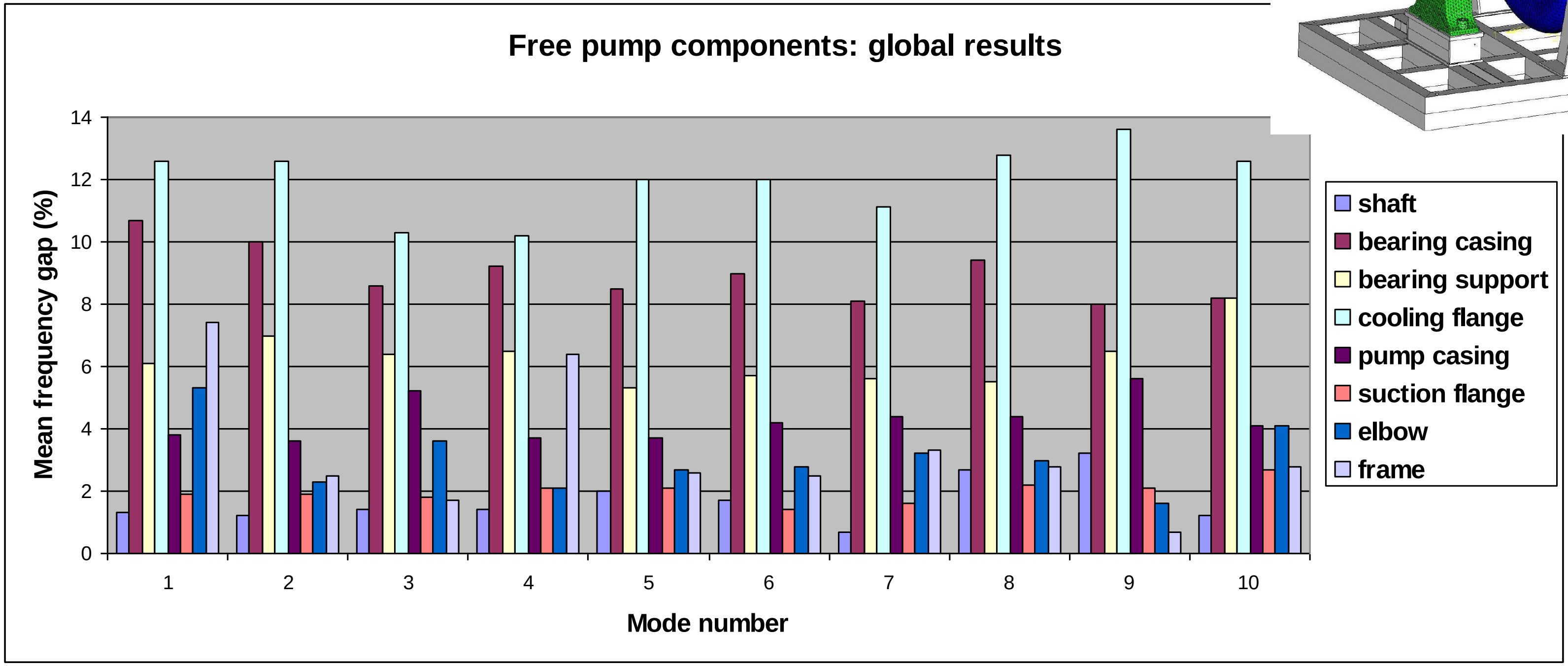
Observation of the numerical variability: the comprehensive approach



Variability of separate pump component eigenfrequencies (blind results)

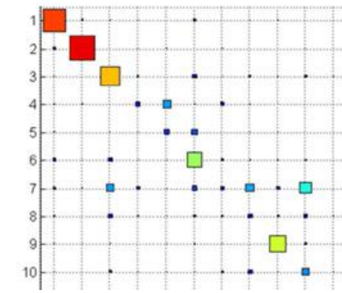
Mean frequency gap (8 to 10 results): $$M = \frac{1}{n}\sum_{i=1}^{n}\left|x_i - \bar{x}\right|$$





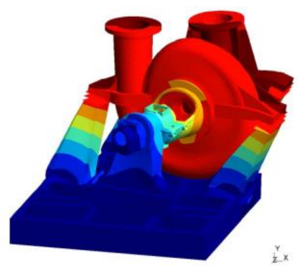
Eigenfrequency variability is mainly related to variability on material characteristics (cast iron) and complex component geometries

MAC (400 kpts)

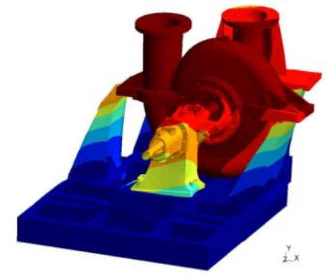


Pairing 2 modal bases of non connected pump

Mode 1 : flexion along horizontal transversal axis



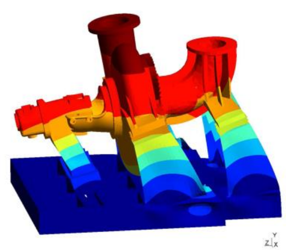
76.9 Hz



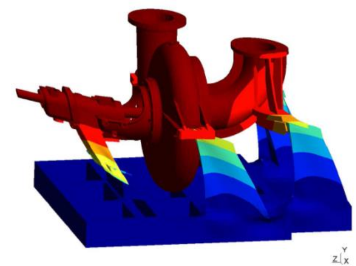
64.2 Hz

MAC = 0.81

Mode 2 : flexion along rotor axis



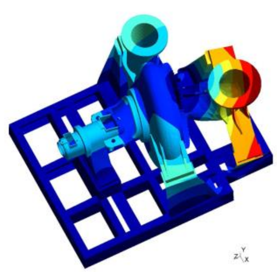
86.1 Hz



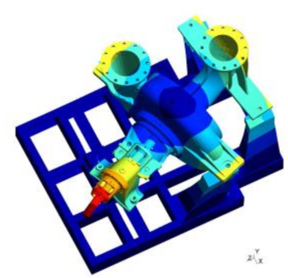
64.6 Hz

MAC = 0.88

Mode 3 : global torsion mode around horizontal transversal axis



154.0 Hz

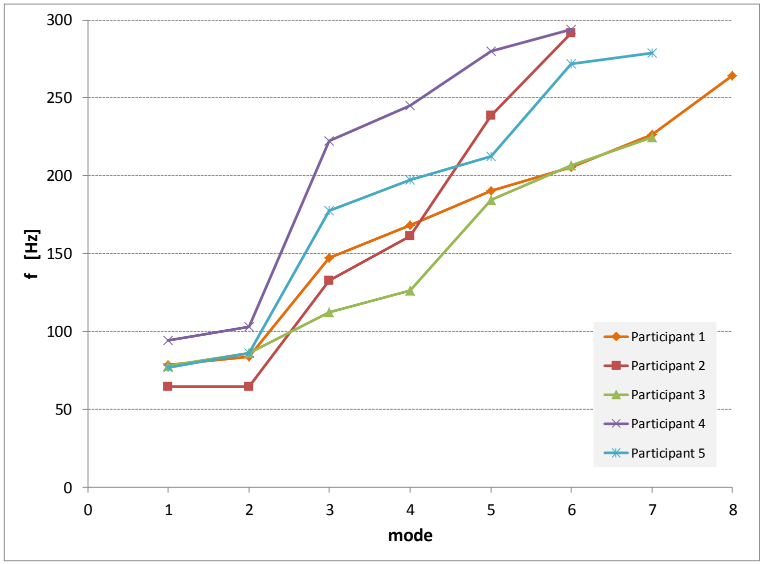


112.5 Hz

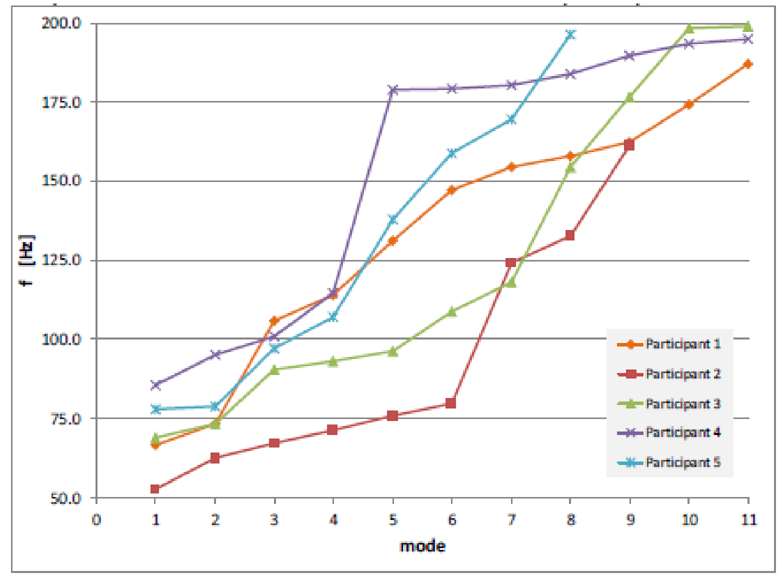
MAC = 0.69

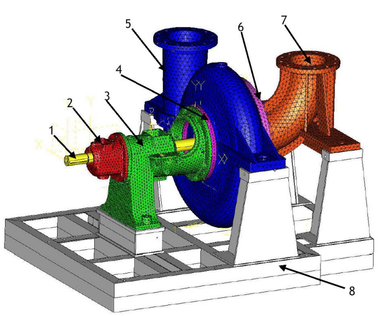
Variabilité numérique

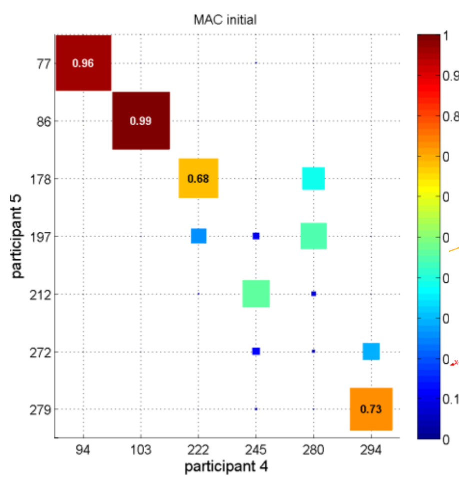
Pompe déconnectée de ses tuyauteries

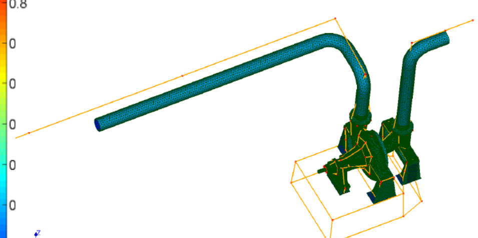


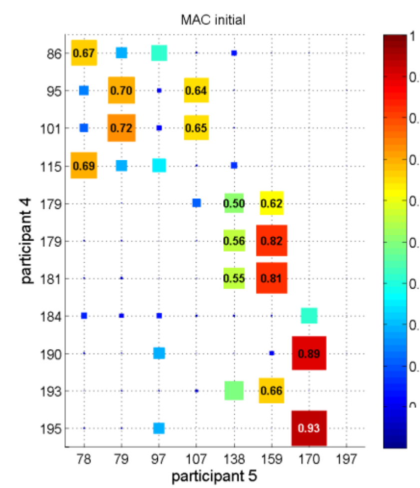
Pompe connectée à ses tuyauteries











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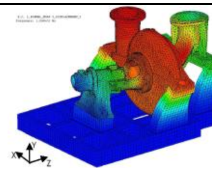
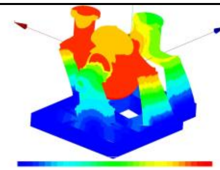
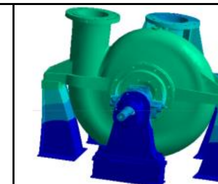
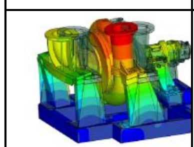
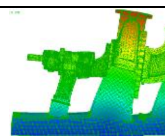
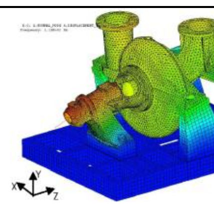
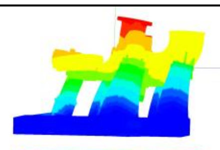
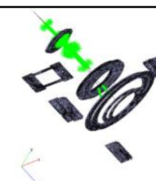
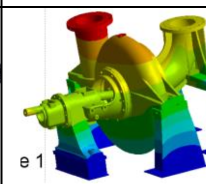
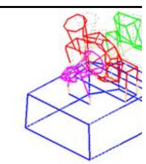
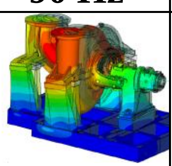
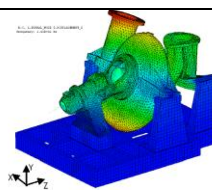
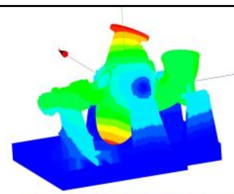
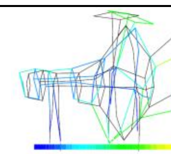
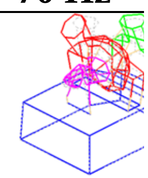
Numerical-experimental correlation on clamped non connected pump assembly (blind results)

Numerical modes						Experimental modes		
				**Picture not available**				Flexion of the pump casing
		109 Hz	**91 Hz**	**71 Hz**	**125 Hz**			
								Flexion along horizontal rotor axis
90 Hz	**45 Hz**	**111 Hz**	**103 Hz**	**88 Hz**	**134 Hz**	**77 Hz**	**70 Hz**	
								Flexion along transversal horizontal axis
92 Hz		**146 Hz**	**178 Hz**	**132 Hz**		**134 Hz**	**152 Hz**	

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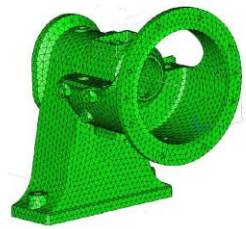
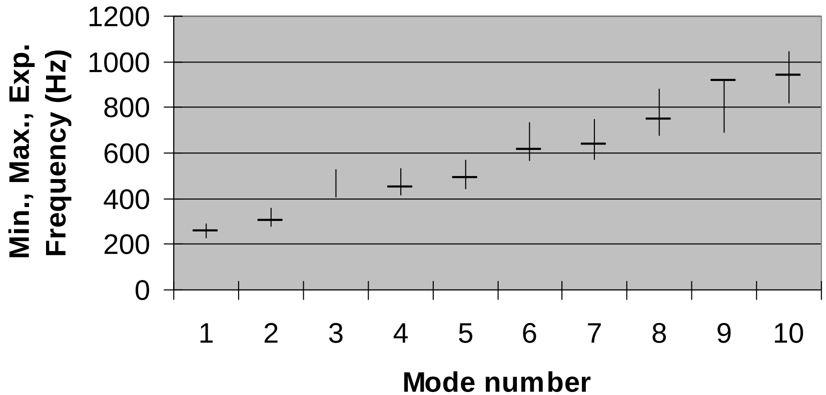
Reliability on modal models of free-free separate components and built-up structures

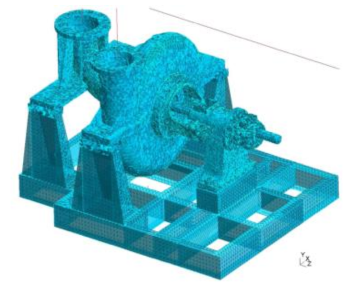
Free-free separate component

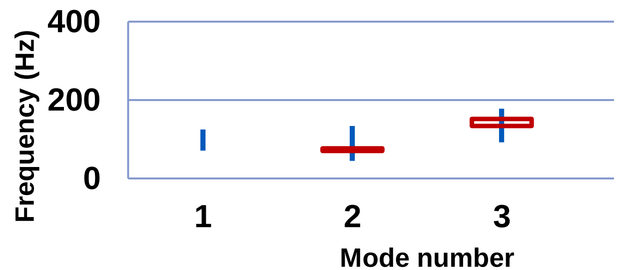




- Narrow numerical variability on eigenmodes (from 2% to 12% depending on components)
- Experimental eigenfrequency values are within the min.-max. numerical eigenfrequency value interval
- The comparison allows criticism relatively to both numerical and experimental results

Clamped built-up equipment





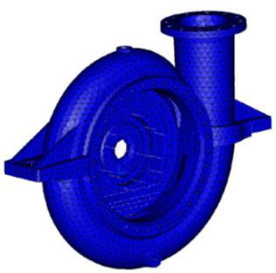
- Pairing operation not trivial
- Variability of blind modal results of the pump assembly: 40% to 43% on 2 modes (larger on superior modes ?)
- The variability essentially comes from the boundary condition and interface connection representations

Reliability on modal models of free-free separate components and built-up structures

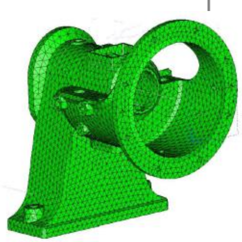
Ability of numerical models to accurately predict the global modal behaviour of a geometrically complex single component

The more complex the structure (number of sub-structures, boundary conditions), the larger the numerical-experimental gap

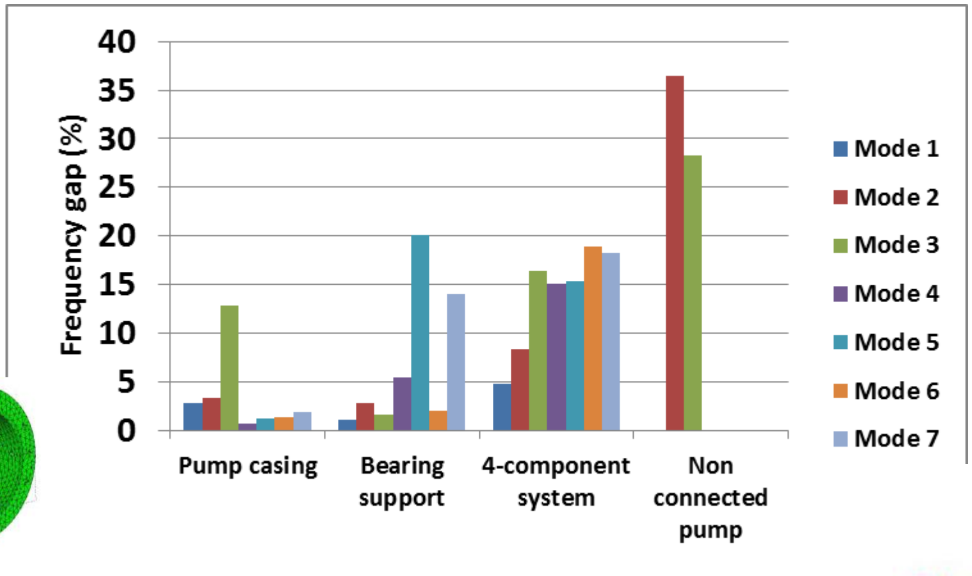
Need of partial experimental information to accurately represent the dynamical behaviour of built-up systems

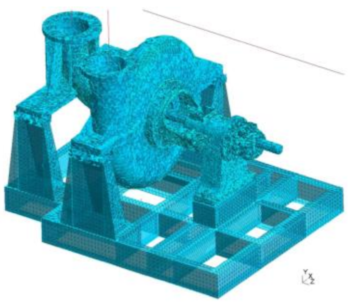


Pump casing

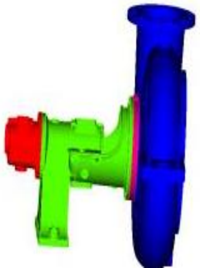


Bearing support





Non connected pump assembly



4-component sub-assembly

L'incertitude numérique totale

Incertitude de modèle

+

Incertitude paramétrique

→ Incertitude numérique totale

Model form uncertainty

- assumptions (linear phenomenon, …)
- geometrical simplifications
- representation of the connections
- representation of boundary conditions
- equations and solver

Parametrical uncertainty

- Material characteristics
- Geometrical dimensions
- Mesh
- Local stiffnesses

Lot 5 : Incertitudes relatives aux simulations numériques

1

- Etudier la faisabilité de méthodes classiques d'estimation des incertitudes paramétriques sur un modèle de structure complexe (assemblage), de grande taille, dans son environnement industriel

2

- Prendre en compte l'incertitude de modèle et estimer l'incertitude totale relative à un calcul modal

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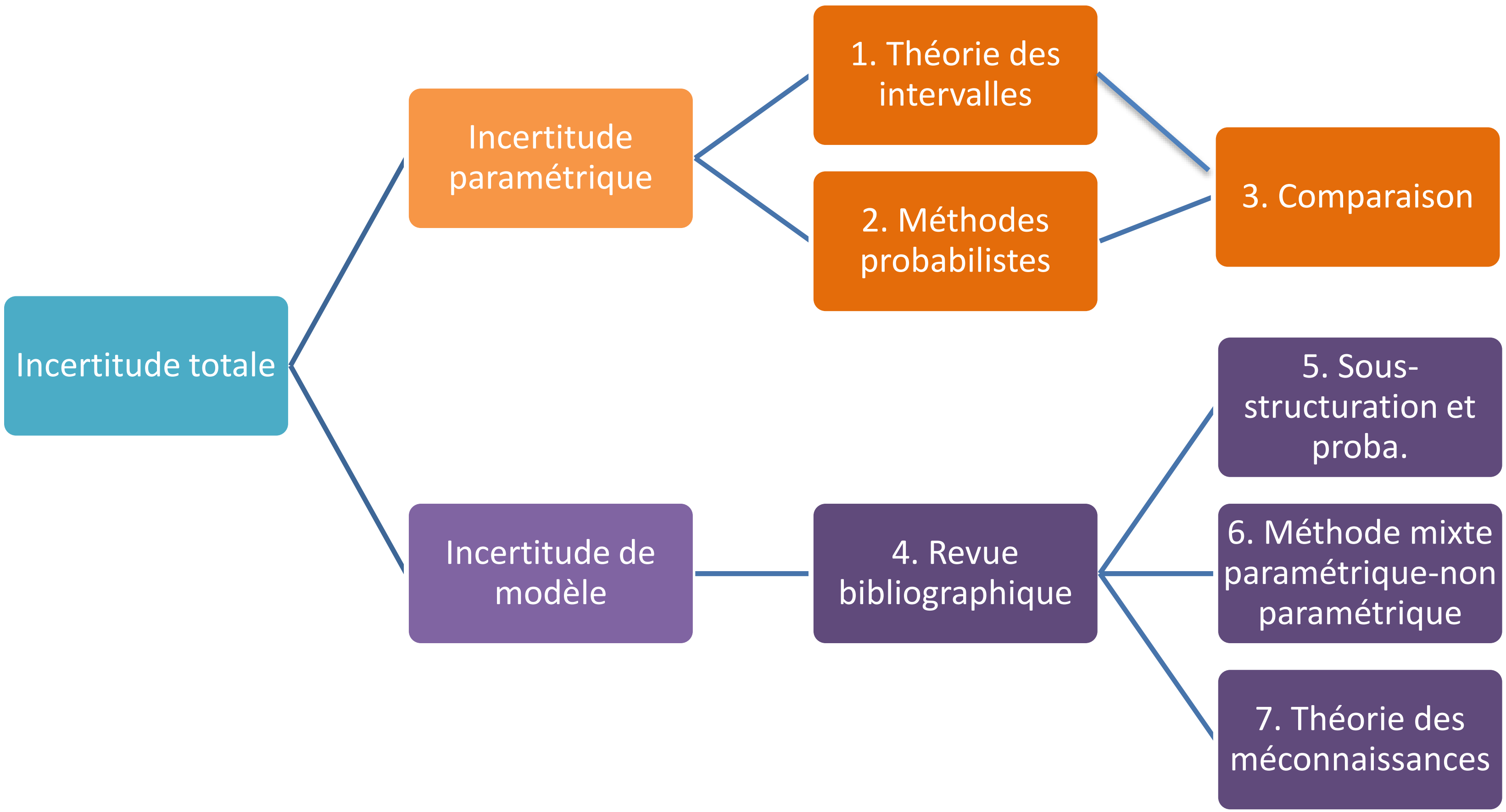
Quantification a priori de l'incertitude numérique totale



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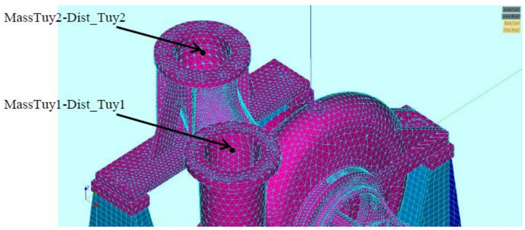
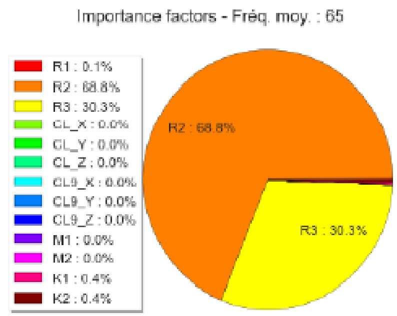
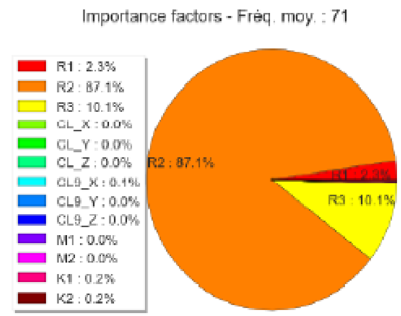
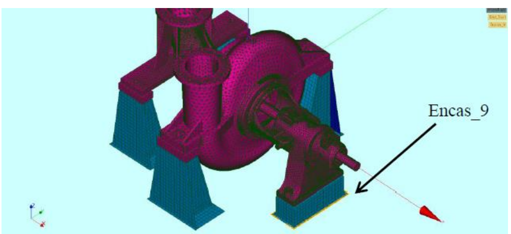
Analyse de sensibilité probabiliste
Exemple : méthode du cumul quadratique



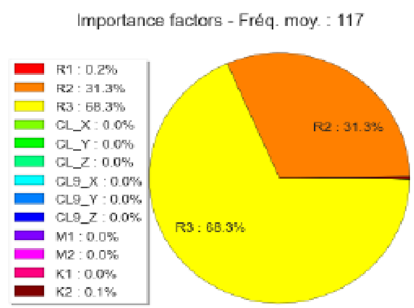
Masses
M1
M2
Raideurs
K1
K2

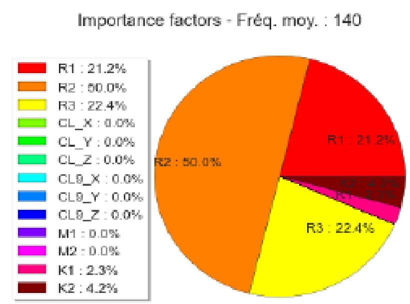


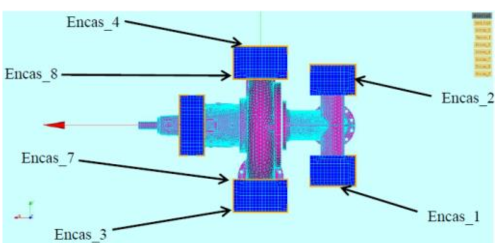




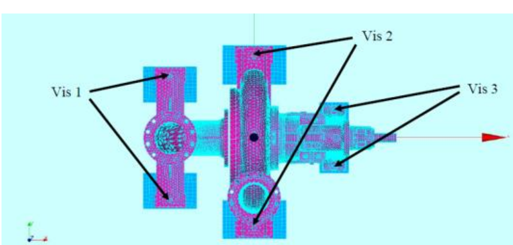
Raideurs
CL9X
CL9Y
CL9Z



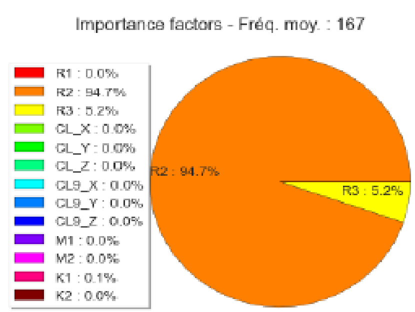


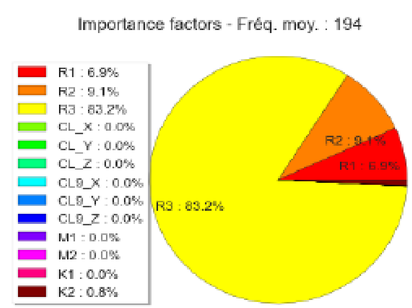


Raideurs
CLX
CLY
CLZ



Rayons des vis
R1
R2
R3





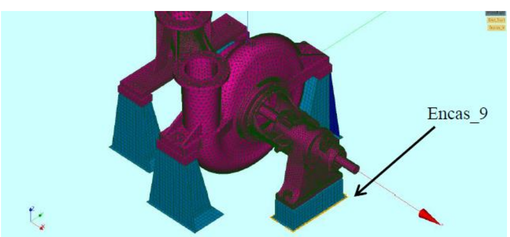
Comparaison méthodes paramétriques Méthodes probabilistes – théorie des intervalles (OpenTurns)

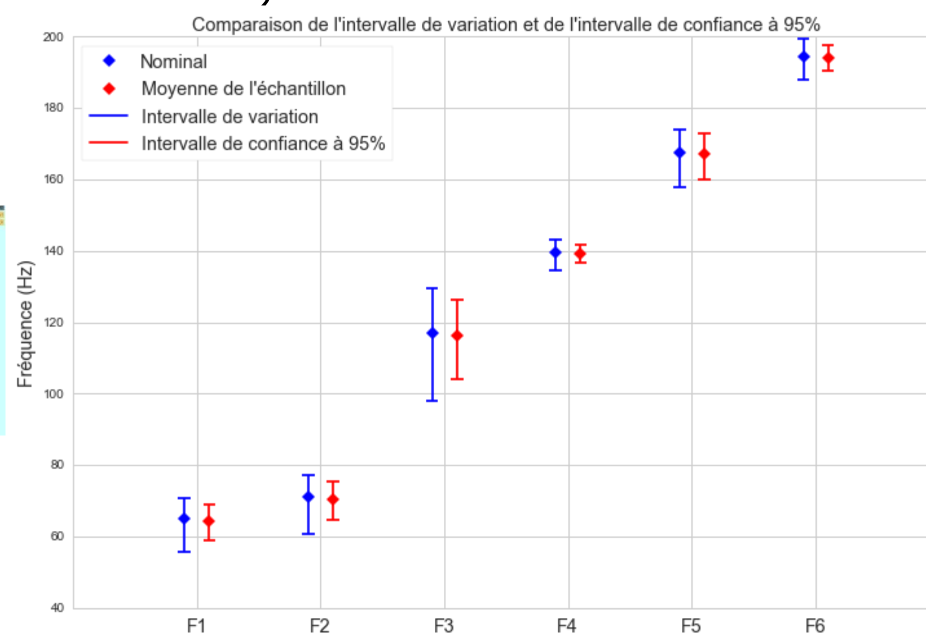
Méthodes probabilistes

- Informations en entrée nécessaires : densités de probabilité des variables aléatoires
- Coûteuse en temps calcul (simulation de Monte Carlo sur méta-modèle)

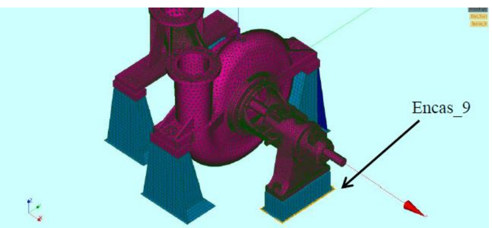
Théorie arithmétique des intervalles

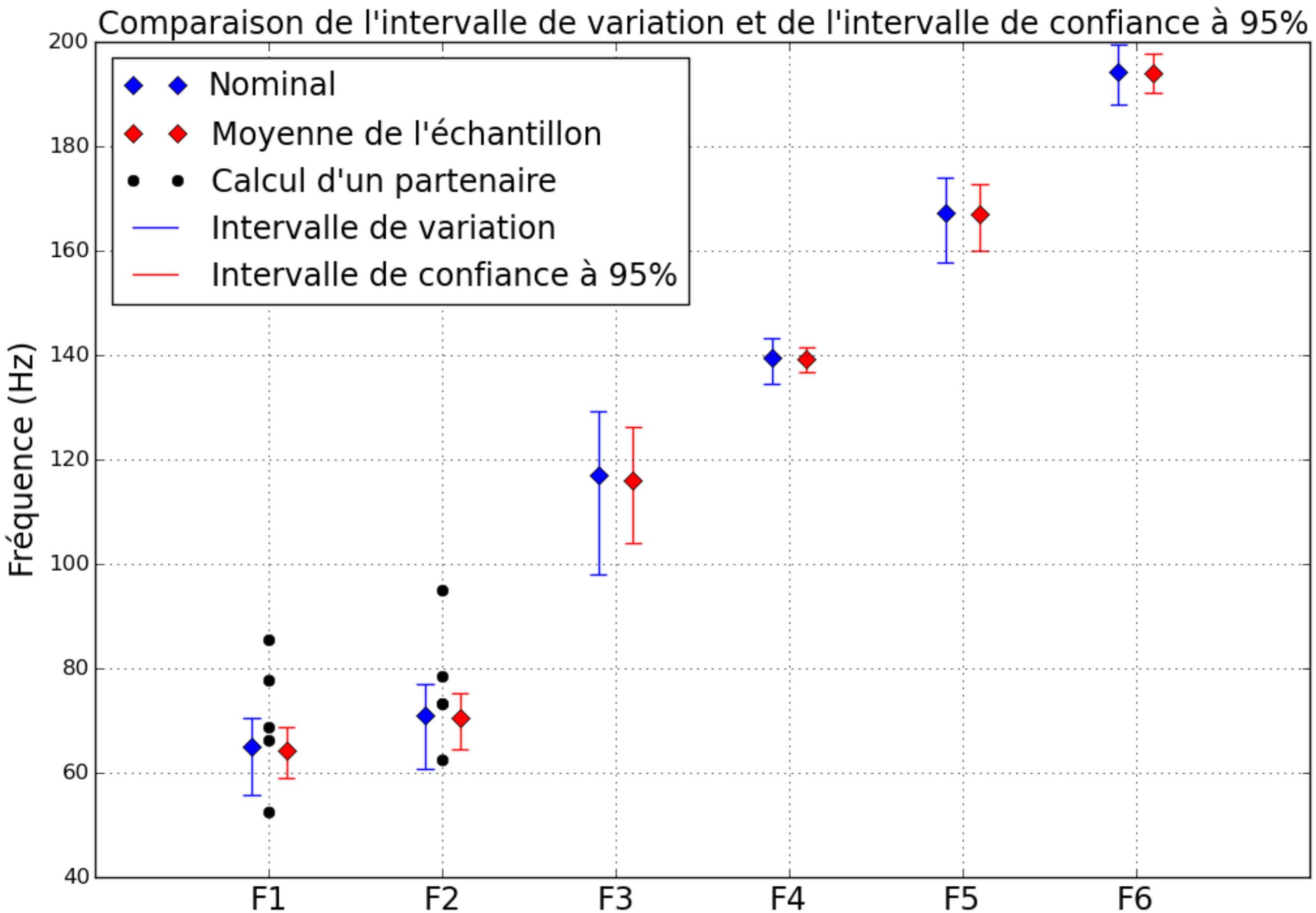
- Informations en entrée nécessaires : bornes de variation des paramètres
- Généralement moins coûteuse en temps calcul





Lot 6 : Confrontation variabilité observée vs incertitude paramétrique estimée

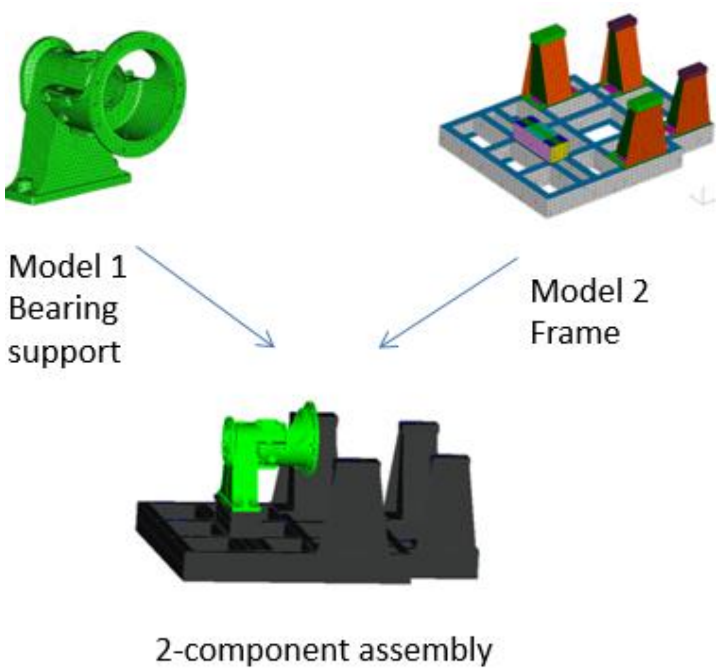




Confrontation possible sur les 2 premiers modes seulement
A modèle fixé, l'incertitude paramétrique sous-estime la variabilité observée
➔ incertitude de modèle, prépondérante, à considérer

SICODYN

Combinaison méthode probabiliste et sous-structuration dynamique



- prise en compte des incertitudes au niveau des modes propres des sous-structures (**fréquences propres**, déformées modales)
- Temps calcul fortement réduit
- Bien adapté aux structures industrielles

Components rigidly connected by two bolts

Free-free two-component system

- variations in component eigenvalues only
- uniform distribution
- variation intervals relative to eigenfrequencies with fixed interfaces deduced from variability observed in the numerical benchmark for sub-structures in free-free configuration
- A Monte Carlo approach with 1000 runs applied in order to estimate eigenfrequency statistics

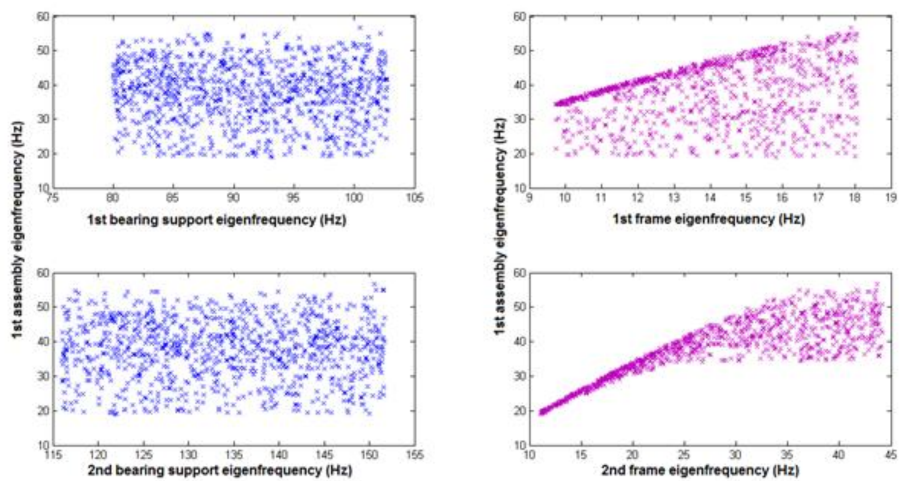
S. Audebert, F. Fall-Lo, Uncertainty analysis on a pump assembly using component mode synthesis, Proceedings M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.). COMPDYN 2013 *4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Kos Island, Greece, 12–14 June 2013.

EDF

Combinaison méthode probabiliste et sous-structuration dynamique

	Bearing support		Frame		2-component assembly	
Mode	Eigenfrequency with fixed interfaces				Free-free eigenfrequency	
	Mean value (Hz)	Coeff. of variation (%)	Mean value (Hz)	Coeff. of variation (%)	Mean value (Hz)	Coeff. of variation (%)
1	91.4	43.2	13.9	103.8	37.6	23.1
2	133.8	46.4	27.6	207.6	48.8	12.8
3	251.1	45.3	35.3	145.3	96.5	6.4
4	262.7	44.3	94.1	69.2	108.7	6.2
5	314.3	43.9	98.9	76.1	116.7	4.6
6	353.1	45.0	103.2	51.9	123.1	3.3
7	523.0	46.7	120.9	44.3	141.7	3.2

First eigenfrequency statistics of the two-component assembly



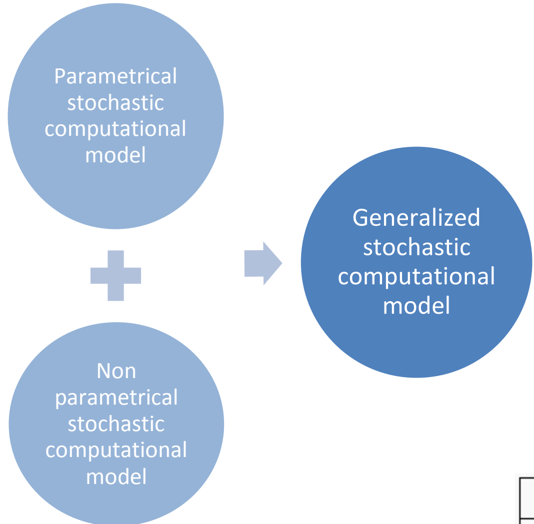
Sensitivity of the first eigenfrequency of the two-component assembly

The variability introduced in intermediate result (eigenfrequency) at component level, instead of simply parametrical uncertainty, is a means to represent the total uncertainty.

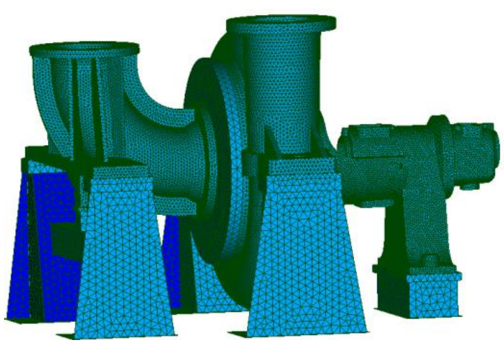
Méthode généralisée paramétrique – non paramétrique

Model-parameters => *i* random variables (mean value μ_i, coeff. variation δ_i)

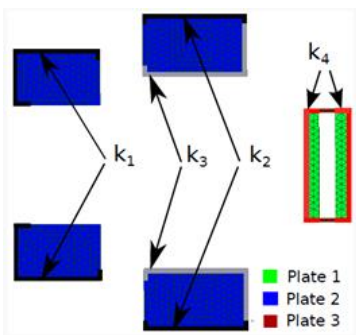
Stiffness matrix *K* Mass matrix *M* => random matrices (δ_K, δ_M)$\in \mathbb{R}^2$



Hyperparameters μ_i, δ_i, δ_K, δ_M identified using experimental data (maximum likelihood method)



Pompe non connectée

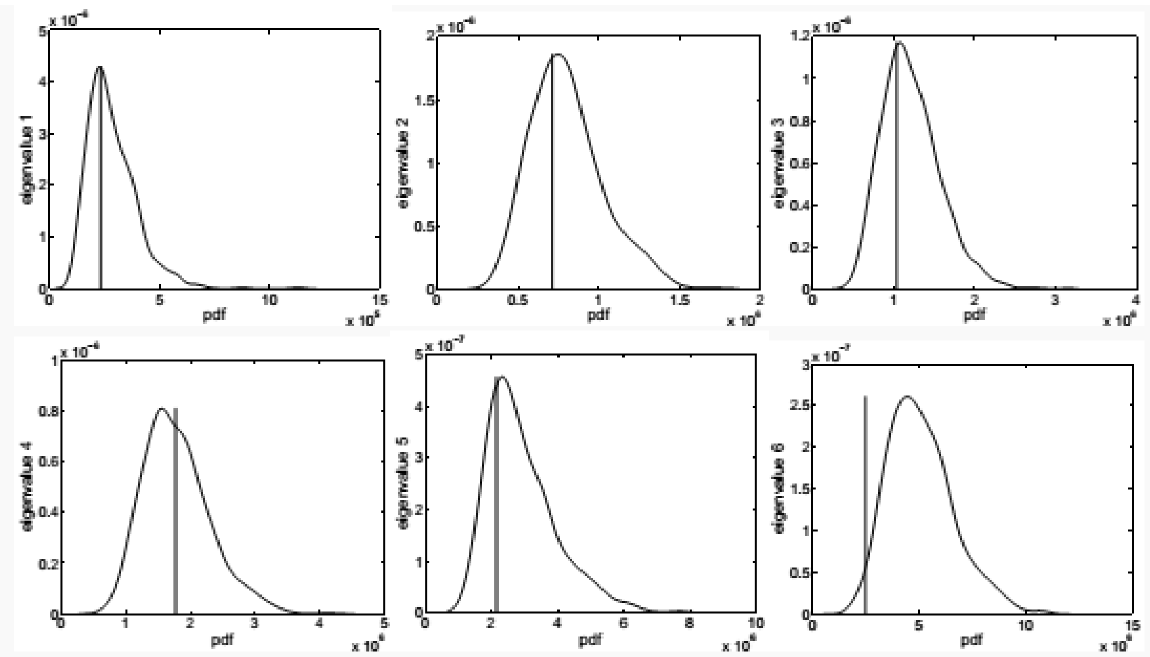


	pdf	Parameters
Young Modulus steel Y_s	Gamma	m_{Y_s} , δ_{Y_s}
Young Modulus cast Y_c	Gamma	m_{Y_c} , δ_{Y_c}
Thickness T_1	Uniform	m_{T_1} , δ_{T_1}
Thickness T_2	Uniform	m_{T_2} , δ_{T_2}
Thickness T_3	Uniform	m_{T_3} , δ_{T_3}
Stiffness K_1	Gamma	m_{K_1} , δ_{K_1}
Stiffness K_2	Gamma	m_{K_2} , δ_{K_2}
Stiffness K_3	Gamma	m_{K_3} , δ_{K_3}
Stiffness K_4	Gamma	m_{K_4} , δ_{K_4}

2 x 9 = 18 hyperparameters relative to model parameters
+ 2 hyperparameters relative to model matrices
=> 20 hyperparameters to identify

A. Batou, C. Soize, S. Audebert, Model identification in computational stochastic dynamics using experimental modal data, *Mechanical Systems and Signal Processing*, 50-51, 307-322 (2015).

Méthode généralisée paramétrique – non paramétrique



- Méthode coûteuse en temps calcul
- Nécessite le calage des hyperparamètres à l'aide de mesures
- Méthode utilisée dans le processus projet chez PSA

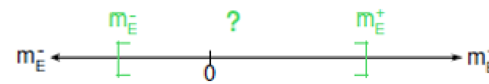
Comparaison fréquences propres mesurées et densité de probabilité

The 5 first experimental eigenfrequencies are predicted with a high probability level.

The 6th experimental eigenfrequency is predicted with a low probability level.

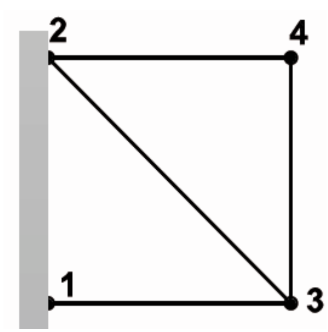
Théorie des méconnaissances LOK

- Intervalles à bornes probabilisées
- Méthode adaptée aux assemblages de sous-structures
- Tout type d'incertitudes (de modèle, paramétriques) globalisées au niveau des sous-structures

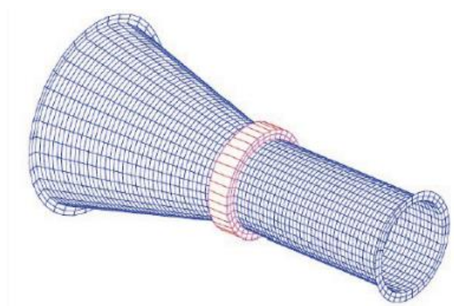


$$-m_E^- \leq m \leq m_E^+$$

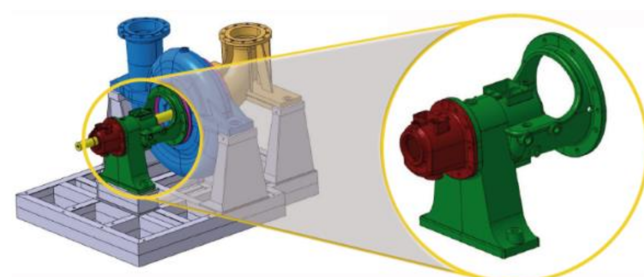
Application à 3 systèmes dynamiques
Extension au cas des fortes méconnaissances



Treillis de barres



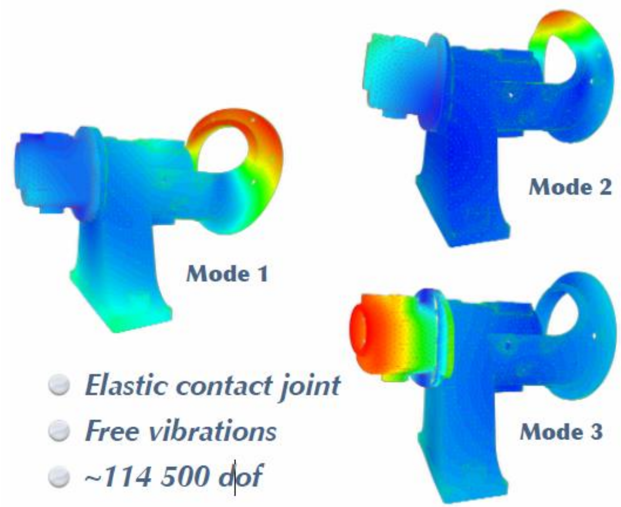
Assemblage cône-cylindre



Assemblage butée et support de palier

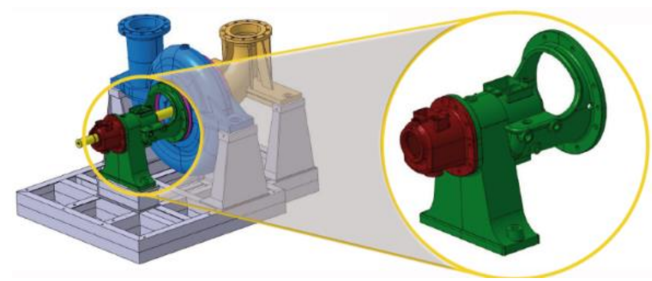
S. Daouk, F. Louf, O. Dorival, L. Champaney, S. Audebert, Uncertainties in structural dynamics: overview and comparative analysis of methods, Mechanics & Industry 16(404) 1-10 (2015).

Théorie des méconnaissances LOK



Large uncertainties

$$E = \overline{E}\ (1 + 0,05\ \eta)$$
$$K_N = \overline{K}_N\ (1 + 0,5\ \eta)$$
$$K_T = \overline{K}_T\ (1 + 0,5\ \eta)$$
$$\eta \sim \mathbb{U}_{[-1;+1]}$$



99%-intervals for 1000 samples

Frequency	Monte Carlo	LOK
396.10 Hz	[364.2 ; 406.0]	[369.5 ; 404.5]
423.32 Hz	[370.6 ; 439.0]	[373.8 ; 435.3]
503.81 Hz	[398.0 ; 590.6]	[401.2 ; 585.4]
	Reference ~253.7 h	**[+0.79 ; -0.88]% ~15 min**

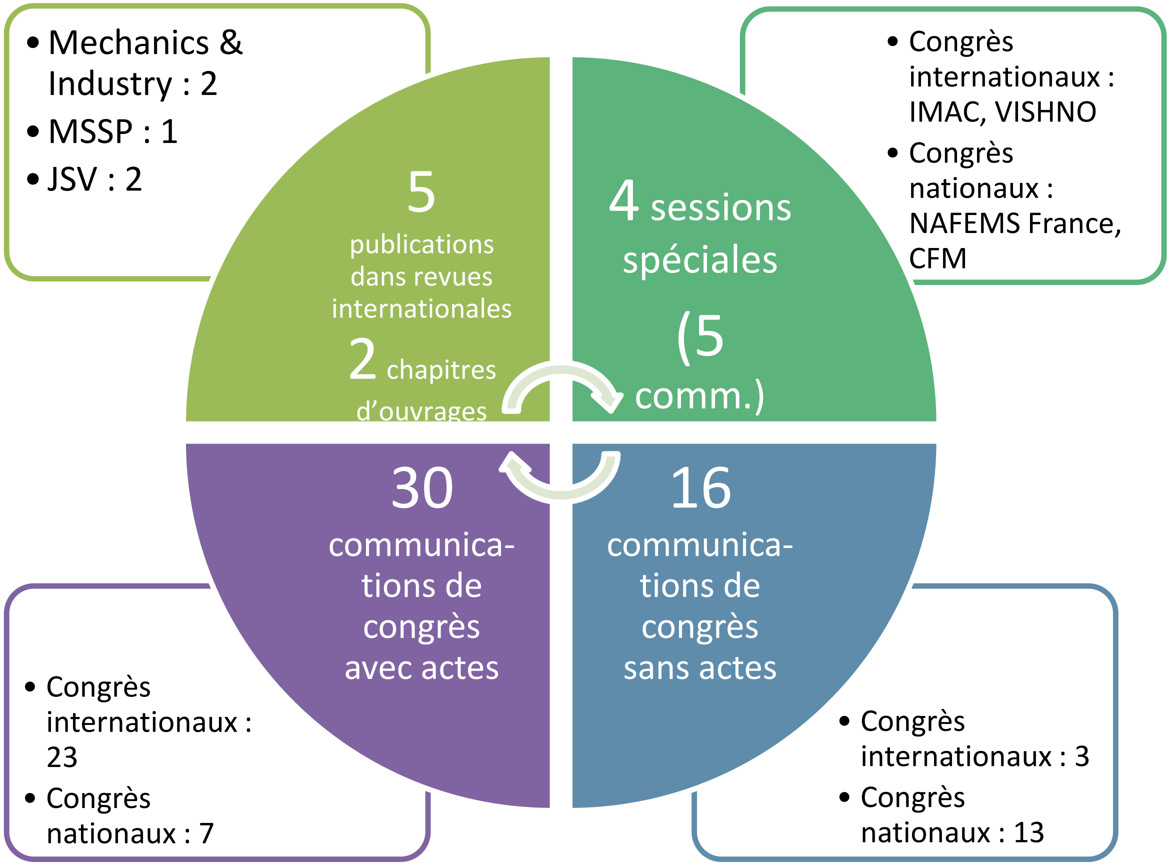
3 premières fréquences propres de l'assemblage butée et support de palier

Méthode adaptée aux structures industrielles
Faible coût de calcul
Interprétation non immédiate

Bilan technique général

- Une démarche complète originale validée via son application postérieure par d'autres laboratoires
  - Observation variabilité numérique (résultats en aveugle)
  - Estimation a priori de l'incertitude numérique totale
  - Confrontation variabilité observée/incertitude estimée
- Des travaux réalisables uniquement dans un cadre collaboratif (benchmarks)
- Pour aller plus loin…
  - Démarche couplée numérique-expérimentale
  - Prise en compte **simultanée** de la fidélité aux données expérimentales et de la robustesse aux incertitudes
  - Elaboration de méthodes **simplifiées** d'estimation a priori des incertitudes
  - Prise en compte systématique de l'incertitude de modèle

Valorisation et dissémination



7 articles
46 communications dont 2 conférences « invité »
1 mémoire de thèse

S. Audebert, SICODYN International Benchmark on dynamic analysis of structure assemblies: variability and numerical-experimental correlation on an industrial pump, *Mécanique et Industries*, 11(6), 439-451 (2010).

S. Audebert, SICODYN International Benchmark on dynamic analysis of structure assemblies: variability and numerical-experimental correlation on an industrial pump (Part 2), *Mechanics & Industry*, 15(1), 1-17 (2014).