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UNCERTAINTY ANALYSIS ON A PUMP ASSEMBLY USING COMPONENT MODE SYNTHESIS

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Abstract. *The combined use of the component mode synthesis and the probabilistic uncertainty analysis is studied on an industrial structure. Component mode synthesis (CMS) methods are useful for the analysis of structures that are built-up of several components. The components are modeled individually and their dynamic models, represented by modal bases, are assembled to produce a much smaller model of the whole structure. In the component mode synthesis framework, uncertainties in properties can be naturally and straightforwardly introduced at the component level; properties concerned can be either component or joint model parameters, such as material characteristics, or component modal characteristics. Variations on component modal characteristics both reflect the model and parametric component uncertainties.*

The structure considered is a free-free two pump component assembly. The whole pump was designed by SULZER Pumps and is used in EDF thermal units. The two frame and bearing support components are assembled using two bolted joints. The variables of interest are the eigenfrequencies of the built-up structure. The uncertain properties are the eigenfrequencies of the two sub-structures: they are modelled in a probabilistic frame as independent random variables defined on intervals determined as a result of 2008-2010 SICODYN international benchmark.

A Monte Carlo approach with 1000 runs is applied in order to estimate eigenfrequency statistics on the built-up structure. The following tendencies can be shown:

- the coefficient of variation of the assembly eigenfrequency values is much lower than the coefficient of variation introduced in the sub-structure eigenfrequency values;

- the first assembly eigenfrequencies depend on the frame eigenfrequencies and not on the bearing support eigenfrequencies, which is a stiffer component.

The present research work has been carried out within the FUI 2012-2015 SICODYN project.

1 INTRODUCTION

A main objective of industrial companies is to quantify the confidence they have in numerical models used either in design purpose or in expertise purpose. The systems of interest include proposed or existing systems that operate at design conditions, at off-design conditions and at failure-mode conditions that apply in accident scenarios. In particular, the dynamical behaviour of engineered systems that equipped power plants must be confidently predicted. The numerical models built to do so in a design purpose must be able to represent the characteristics of the structure itself, its coupling with its environment, the usually unknown excitations and the corresponding error sources and uncertainties; in an expertise purpose, where measurements can be carried out on the existing structure and used to improve the numerical-experimental correlation, the numerical models are generally generic and must be able to reproduce the behaviour of the whole family of nominally-identical structures. The confidence level of a numerical simulation can be quantified by what is called the total numerical uncertainty, which can be divided into parametrical uncertainty and model form uncertainty. Several methodologies such as the probabilistic, interval or possibilistic analyses are commonly used to a priori determine the uncertainty related to output quantities of interest due to input parameter error or uncertainty. Quantifying the model form uncertainty is not so developed and is generally undirectly performed.

The combined use of the component mode synthesis and the probabilistic uncertainty analysis is a possible way to estimate the total numerical uncertainty. Component mode synthesis (CMS) methods are useful for the analysis of structures that are built-up of several components. The components are modeled individually and their dynamic models, represented by modal bases, are assembled to produce a much smaller model of the whole structure. In the component mode synthesis framework, uncertainties in properties can be naturally and straightforwardly introduced at the component level; properties concerned can be either component or joint model parameters, such as material characteristics, or component modal characteristics. Variations on component modal characteristics both reflect the model and parametric component uncertainties. The method has been presented and tested on academic test cases in [1]; it is here applied on an industrial built-up structure.

After the FUI SICODYN 2012-2015 project is presented, the uncertainty analysis in the framework of component mode synthesis is described. Uncertainty quantification and propagation are applied in view of modal characterisation of a built-up two-component pump assembly. Following are quantitative results and concluding remarks.

2 THE 2012-2015 FUI SICODYN PROJECT

The financed FUI (Fonds Unique Interministériel) project, untitled SICODYN (pour des Simulations crédibles via la COrrélation calculs-essais et l'estimation d'incertitudes en DYnamique des structures) is based on an a complex built-up demonstrator in industrial environment ; it gathers 13 French partners, which are industrials, academic, and small and medium size enterprises (cf. Appendix 1).

2.1 Scientific structuration

The idea underlying the project is to give easy tools, based on tested methodologies, to a priori estimate the confidence associated to a dynamical simulation-based prediction [1, 6]. The general organisation of the 6 parts of the project is described in Fig. 1. In Part 1, an inventory of the benchmarks in structure dynamics and a review of methods which estimate the total uncertainty (model parameter uncertainty plus model form uncertainty) will be made. Two benchmarks (Parts 2 and 3) will permit to observe the total numerical variability, as in the preceeding SICODYN benchmark [7-9], and the experimental variability, related to nominally-identical structures [10], or different operators. Part 4 will be devoted to test-analysis correlation, using notably a collection of numerical results and a collection of experimental measurements [11]. In Part 5, both parametric and non parametric methods will be confronted in order to quantify the uncertainties, either in a deterministic (method of intervals…) or probabilistic context [12-17].

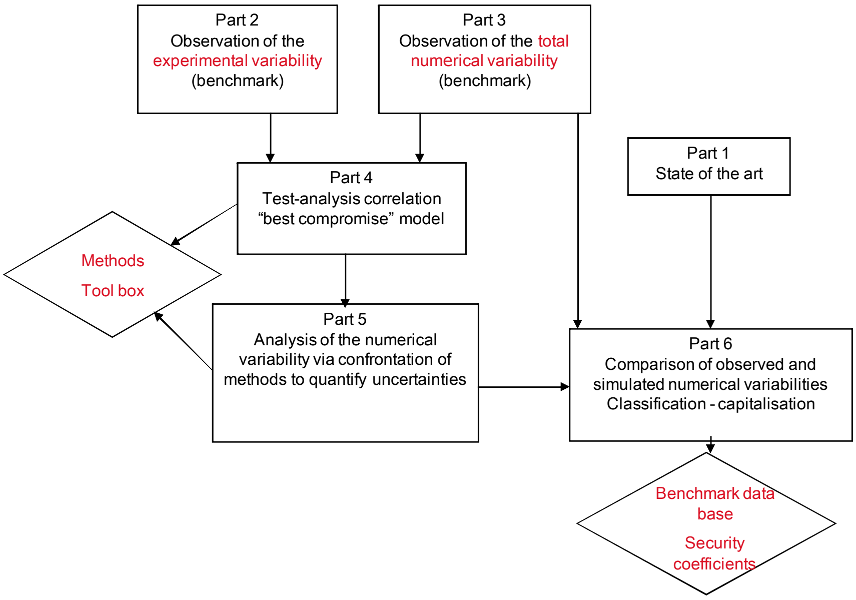

Figure 1: Organisation of the 6 parts of the SICODYN project

In Part 6, the observed (via the benchmark) and simulated (in Part 5) numerical variabilities will be compared. The most appropriate methods, from an industrial point of view, will be retained and possibly derived in simple security coefficients and margins applied in classes of dynamical problems to determine.

2.2 Description of the demonstrator

The chosen equipment is a pump used in EDF thermal units (Fig. 2). It is a one-stage booster pump, composed of a diffuser and a volute, with axial suction and vertical delivery (body with volute called "snail"), mounted on a metallic frame. It was designed forty years ago by Sulzer Pumps.

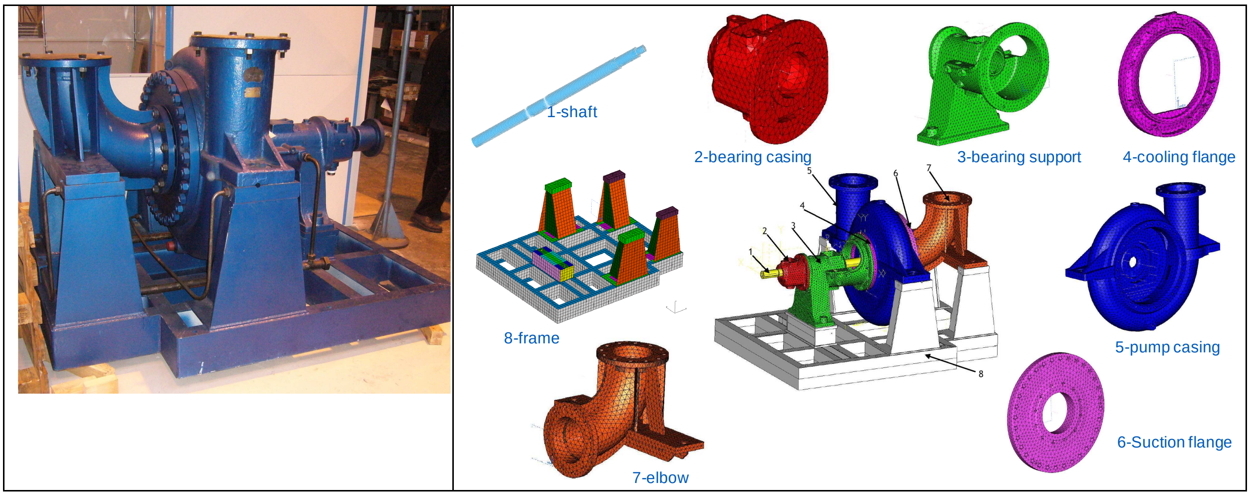

Figure 2: The pump assembly and its main components

3 UNCERTAINTY ANALYSIS AND COMPONENT MODE SYNTHESIS

The component mode synthesis as a framework for uncertainty analysis has been described and applied on academic examples in [1]. The component mode synthesis is a well adapted method to numerically analyse structures that are built-up of several components, as is generally the case in industrial applications. The components are modeled individually and their dynamic models, represented by modal bases, are assembled to produce a much smaller model of the whole structure, and so less time consuming simulations.

A first benefit is, in the context of analysis of structures with uncertain properties, that the computer time related to repeated deterministic problems is drastically reduced, which allows to take into account the statistical independency of the components and the joints. As a consequence, reanalysis, only required for uncertain elements, is less time consuming.

The second benefit is that uncertainties in properties can be naturally and straightforwardly introduced at the component level; properties concerned can be either component or joint model parameters, such as material characteristics, or component modal characteristics. What is making a distinction between well-known methods to estimate parametrical uncertainty estimation and the present methodology is that variations on component modal characteristics both reflect the model and parametric component uncertainties. In that way, it constitutes an original means to take into account the model form uncertainty. Furthermore, one can have a precise idea of the uncertainties related to modal component characteristics, directly issued for instance from variability observed via a numerical benchmark.

Third qualitatively different uncertainty descriptions can be combined, with some components being described probabilistically, some possibilistically. This method has been applied in [1] on an academic test-case.

4 MODAL CHARACTERISATION OF A TWO-COMPONENT PUMP ASSEMBLY USING COMPONENT MODE SYNTHESIS

The dynamical system studied is the assembly of the bearing support and the frame, respectively made of cast iron and steel: their CAD models are shown in the Figure 3. The components are rigidly connected to each other by two bolts; the two-component system is considered in a free-free configuration.

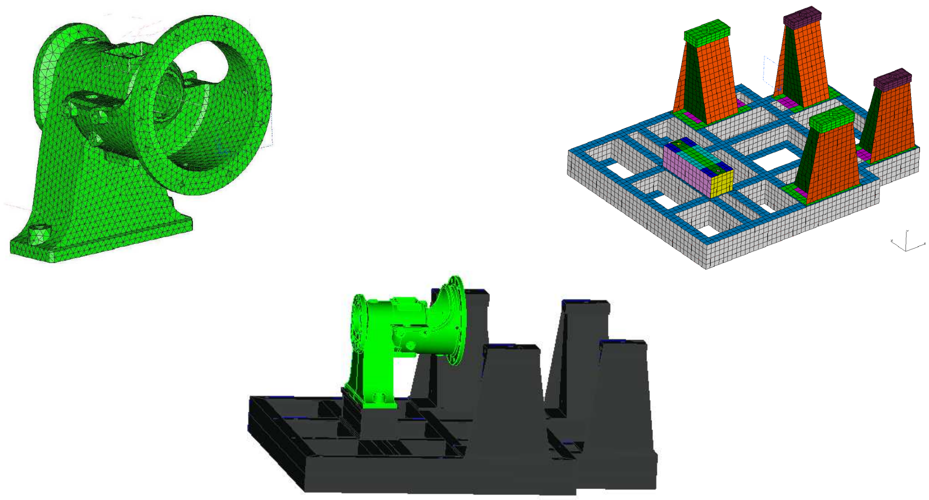

Figure 3: Bearing support and frame CAD models, two-component pump assembly

The modal analysis using component mode synthesis has been carried out with 30 Craig-Bampton interface modes and 20 modes with fixed interfaces for each component. Corresponding modal results are validated by comparison with results issued from direct simulation: the eigenfrequency gap is about 0.1% on the 14 first modes (maximum is 0.2% on the second mode) and the MAC correlation is excellent, as the diagonal MAC values are greater than 0.99 (see Figure 4).

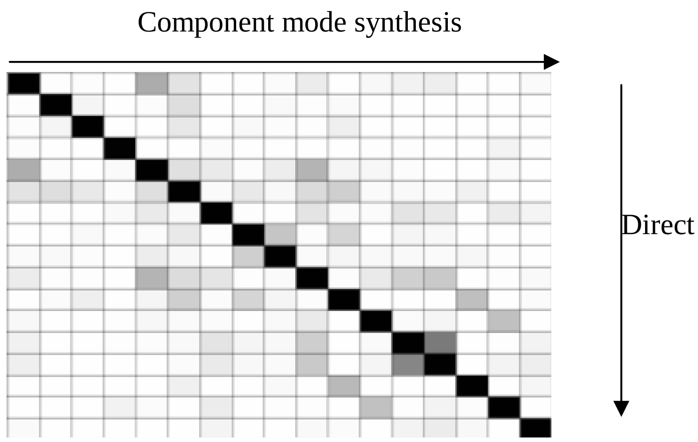

Figure 4: MAC matrix (direct / component mode synthesis)

5 UNCERTAINTY QUANTIFICATION AND PROPAGATION

Uncertainty analysis is performed considering variation in component eigenvalues only, which are supposed to follow a uniform distribution. The variation intervals relative to eigenfrequencies with fixed interfaces have been deduced from variability observed in the numerical benchmark for sub-structures in free-free configuration [7-9].

A Monte Carlo approach with 1000 runs was applied in order to estimate eigenfrequency statistics. Table 1 shows the first eigenfrequency statistics of the two-component assembly function of the eigenfrequency statistics of the components. It can be seen that the coefficient of variation (i.e. ratio of the mean standard deviation to the mean value) of the assembly eigenfrequency values is much lower than the variation coefficient introduced in the substructure eigenfrequency values.

Mode number	Bearing support		Frame		Two-component assembly	
	Eigenfrequency with fixed interfaces				Free-free eigenfrequency	
	Mean value (Hz)	Coefficient of variation (%)	Mean value (Hz)	Coefficient of variation (%)	Mean value (Hz)	Coefficient 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

Table 1: First eigenfrequency statistics of the two-component assembly function of the eigenfrequency statistics of the components

The sensitivity of the first eigenfrequency of the two-component assembly function of the first two eigenfrequency values of the bearing support and the frame is illustrated in Figure 5. The point cloud shows that there is no dependence of the first eigenfrequency of the assembly function of the bearing support eigenfrequencies; this conclusion is generalized to the other assembly eigenfrequencies.

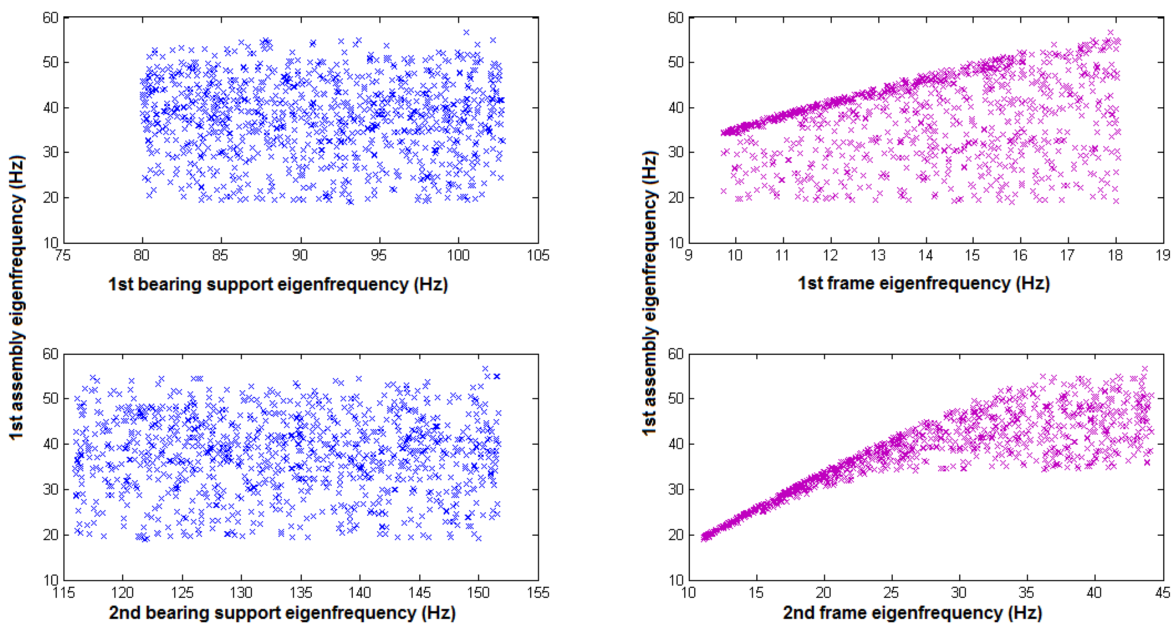

Figure 5: Dependency of the 1st assembly eigenfrequency on the two first component eigenfrequencies

On the other hand, the dependency function of the frame eigenfrequencies is obvious: the first and second assembly eigenfrequencies depend on the two first frame eigenfrequencies (cf.

Fig. 6), the third one depends on the 4th frame eigenfrequency and the fourth one depends on the 3rd frame eigenfrequency. This is related to the fact that the bearing support is much stiffer than the frame, so that the dynamical behaviour of the two-component assembly is essentially directed by the dynamical behaviour of the frame. This indicates that the modal characteristics of the frame must be the more possible precisely determined before studying the modal behaviour of the two-component assembly.

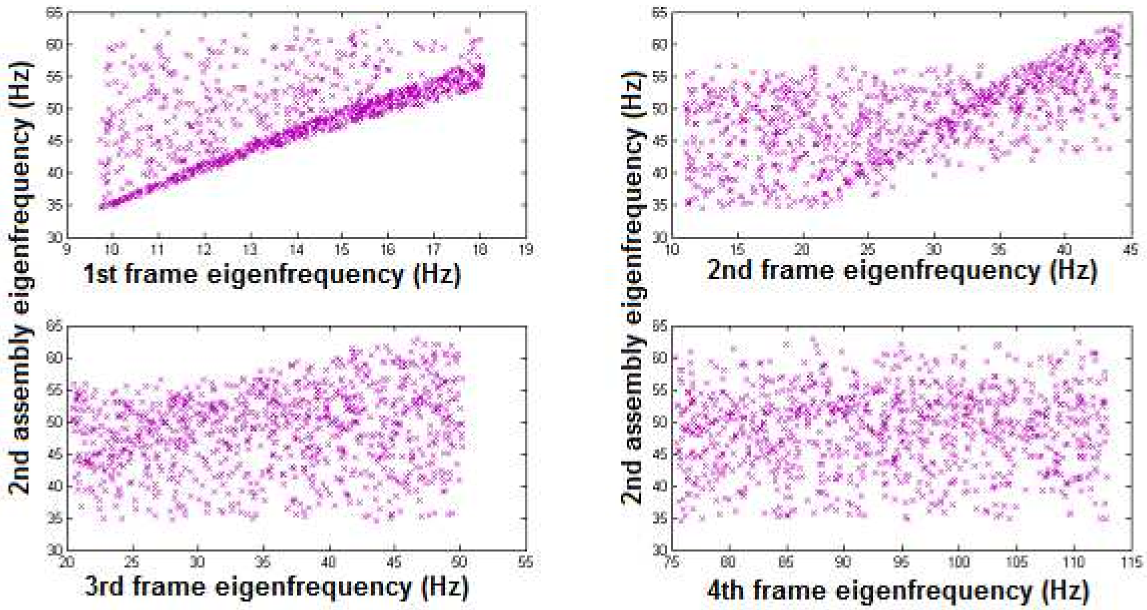

Figure 6: Dependency of the 2nd assembly eigenfrequency on the four first frame eigenfrequencies

6 CONCLUSIONS

The component mode synthesis as a framework for uncertainty analysis, which has been previously described and applied on academic examples in [1], is here tested on an industrial built-up structure. Uncertainty analysis is performed considering variation in component eigenvalues, whose variation intervals have been directly deduced from variability observed in about ten different models built in a previous numerical benchmark. The variability introduced in intermediate result (eigenfrequency) at component level, instead of simply parametrical uncertainty, is a means to represent the total uncertainty, which both reflects the model and parametric component uncertainties.

The application of this framework on a two-component dynamical system permits to show that the dynamical behaviour of the built-up structure is but determined by one sub-structure (frame); furthermore, the dependency of its first eigenfrequency values on the first frame eigenfrequencies can be established. The statistics on the 1000 runs performed give the useful information that the coefficient of variation of the assembly eigenfrequency values is much lower than the coefficient of variation introduced in the frame eigenfrequency values.

Following research will concern the introduction of modeshapes and connection conditions as uncertain properties. When applied to the full pump assembly, comparison with observed variabilities within the benchmark can be performed.

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REFERENCES

[1] L. Hinke, F. Dohnal, B.R. Mace, T.P. Waters, N.S. Ferguson, Component mode synthesis as a framework for uncertainty analysis, *Journal of Sound and Vibration*, 324, 161-178, 2009.

[2] C.J. Roy, W.L. Oberkampf, A comprehensive framework for verification, validation, and uncertainty quantification in scientific computing, *Comput. Methods Appl. Mech. Engrg*. 200 (2011) 2131-2144.

[3] C. Unal, B. Williams F. Hemez, S.H. Atamturktur, P. Mc Clure, Improved best estimate plus uncertainty methodology, including advanced validation concepts, to licence evolving nuclear reactors, *Nuclear Engineering and Design* 241 (2011) 1813-1833.

[4] S. Atamturktur, F. Hemez, B. Williams, C. Tome, C. Unal, A forecasting metric for predictive modelling, Computers and Structures 89 (2011) 2377-2387.

[5] J.R. Langenbrunner, F.M. Hemez, J.M. Booker, T.J. Ross, Model choice considerations and information integration using analytical hierarchy process, Sixth International Conference on Sensitivity Analysis of Model Output, *Procedia Social and Behavioral Sciences* 2 (2010) 7700-7701.

[6] M. Pilch, T.G. Trucano, J.C. Helton, Ideas underlying the quantification of margins and uncertainties, *Reliability Engineering and System Safety* 96 (2011) 965-975.

[7] 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.

[8] S. Audebert, I. Zentner, A. Mikchevitch, Variability and propagation of uncertainties on modal simulations of a built-up structure (SICODYN benchmark), *EURODYN 2011*, Leuwen, Belgium, 4-6 July 2011.

[9] S. Audebert, SICODYN International benchmark on dynamic analysis of structure assemblies: variability and numerical-experimental correlation on an industrial pump (part 2), *XVIIIe Symposium « Vibrations Chocs et Bruit & ASTELAB»*, Clamart, 03-05 July 2012.

[10] A. Batou, C. Soize, M. Corus, Experimental identification of an uncertain computational dynamical model representing a family of structures, *Computers and Structures* 89 (2011) 1440-1448.

[11] Oberkampf W.L., Barone M.F. (2006), Measures of agreement between computation and experiment: validation metrics, *Journal of Computational Physics* 217, 5-36.

[12] B. Van den Nieuwenhof, J.P. Coyette, Modal approaches for the stochastic finite element analysis of structures with material and geometry uncertainties, *Comput. Methods Appl. Mech. Engrg*. 192 (2003) 3705–3729.

[13] D.C. Kammer, S. Nimityonggskul, Propagation of uncertainty in test-analysis correlation of substructured spacecraft, *Journal of Sound and Vibration* 330 (2011) 1211-1224.

[14] M. Guedri, S. Cogan, N. Bouhaddi, Robustness of structural reliability analyses to epistemic uncertainties, *Mechanical Systems and Signal Processing* 28 (2012) 458-469.

[15] A.K. Der Kiureghian, O. Ditlevsen, Aleatory or epistemic? Does it matter?, *Structural Safety* 31 (2009) 105-111.

[16] Hinke L. (2008), Modelling approaches for the low-frequency analysis of built-up structures with non-deterministic properties, *Master Thesis*, University of Southampton, Faculty of Engineering, Science and Mathematics, Institute of Sound and Vibration Research, April 2008.

[17] B.R. Mace, P.J. Shorter (2001), A local modal perturbational method for estimating frequency response statistics of built-up structures with uncertain properties, *Journal of Sound and Vibration* 242(5), 793-811.

Appendix 1

The 13 partners currently involved in 2012-2015 SICODYN project are:

ASTRIUM Space Transportation

CETIM

EDF R&D

LMT ENS Cachan

Institut FEMTO-ST UMR CNRS 6174

LAMCOS UMR CNRS 5259 INSA Lyon

NECS Numerical Engineering and Consulting Service

PHIMECA Engineering

SAMTECH

SOPEMEA

SULZER Pompes France

MSME UMR-CNRS 8208

VIBRATEC