Chapter 16
SICODYN Research Project: Variability and Uncertainty in Structural Dynamics

Sylvie Audebert

Abstract The idea underlying the SICODYN (SImulations credibility via test-analysis COrrelation and uncertainty quantification in structural DYNamics) funded research project is to give easy tools, based on tested methodologies, to a priori estimate the confidence associated to a dynamical simulation-based prediction. The project is based on a complex built-up pump in industrial environment. Gathering 13 French academic and industrial partners, it is organized in 6 parts. In Part 1, an inventory of the benchmarks in structure dynamics and a review of methods leading to credible models are performed. Experimental benchmarks based on in-situ measurements permit the quantification of experimental variability, related to nominally-identical structures or due to operator and modal identification methodology (Part 2). Numerical benchmarks (Part 3) lead to observe the corresponding total numerical variability. Part 4 is devoted to test-analysis correlation methods. In Part 5, both parametric and non parametric methods are confronted in order to quantify the parametrical and model-form uncertainties, either in a deterministic (method of intervals . . .) or probabilistic context. The objective of Part 6 is to estimate the capacity of uncertainty quantification methods to represent the observed numerical variability, and to select, or adapt, some of them, to propose simple tools usable in industrial context.

Keywords Vibrating mechanics • Numerical and experimental benchmarks • Modal characteristics • Uncertainty quantification

16.1 Context and Objectives

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 equip 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, when 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.

16.2 Scientific Structuration of SICODYN Project

The funded FUI (Fonds Unique Interministériel) 2012–2016 project, untitled SICODYN, follows the international 2008–2010 SICODYN benchmark [1, 2]. It is based on a complex built-up demonstrator in industrial environment. The project gathers 13 French academic and industrial partners [3].

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 [4–7]. The general organization of the six interconnecting parts of the project is described in Fig. 16.1. The quantities of interest are the modal characteristics of the mechanical system (eigenfrequency, modeshape and modal damping). In Part 1, an inventory of the benchmarks in structure dynamics and a

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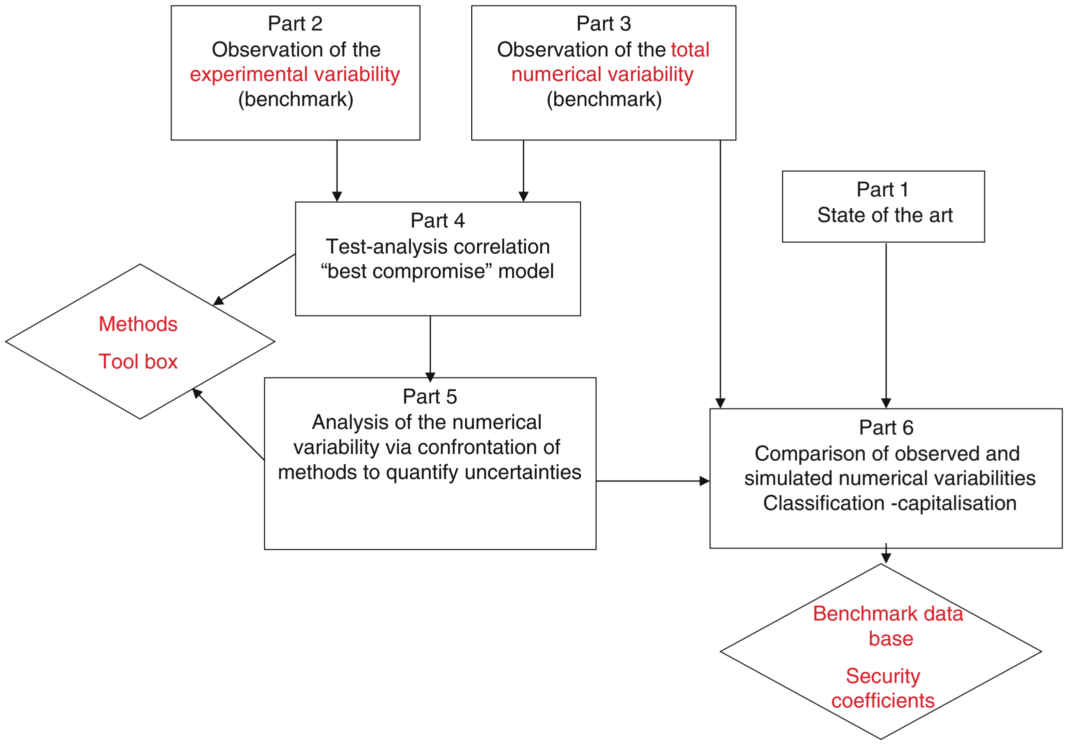

Fig. 16.1 Organization of the six parts of the SICODYN project

review of methods leading to credible models are performed: test-analyses methods and ways to estimate the total uncertainty. In Part 2, experimental benchmarks based on laboratory and in-situ measurement campaigns permits the quantification of experimental variability, related to nominally-identical structures or due to operator and modal identification methodology. In addition, two laboratory devices are designed and used in order to improve and validate the numerical representation of a bolted assembly at macro-level. A numerical benchmark (Part 3) on the pump assembly considered in its work environment (complex boundary conditions that are frame fixed in concrete and connections with suction and delivery pipes) leads to observe the total numerical variability, which takes into account the parametric and model form uncertainty. Part 4 is devoted to test-analysis correlation and model updating, using notably a collection of numerical results and a collection of experimental measurements [8]. Methods to elaborate the best-estimate model, which both insures fidelity to measured data and robustness relatively to uncertainties, are comparatively tested. In Part 5, both parametric and non parametric methods are confronted in order to quantify the uncertainties, either in a deterministic (method of intervals . . .) or probabilistic context [9–11]. In Part 6, the observed (via the benchmark) and simulated (in Part 5) numerical variabilities will be compared. The most appropriate uncertainty quantification methods to a priori represent the observed numerical variability, from an industrial point of view, will be selected and possibly derived in simple security coefficients and margins applied in classes of dynamical problems to determine, or simple tools usable in industrial context.

16.3 Description of the Demonstrator

The chosen equipment is a pump used in EDF thermal units (Fig. 16.2). 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 40 years ago by Sulzer Pumps. The bolted built-up structure contains eight main components.

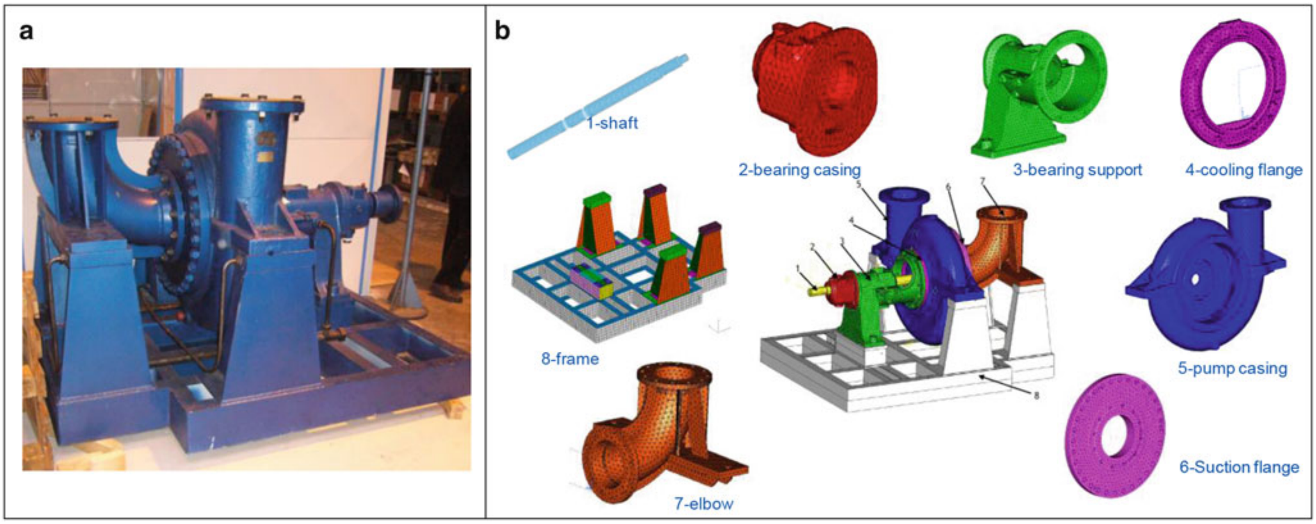

Fig. 16.2 The pump assembly and its main components. (**a**) The pump assembly. (**b**) CAD models of the pump components

16.4 Innovative Characteristics and Technological Challenges

The main innovative characteristics of SICODYN project are following:

- Organization of an experimental benchmark in situ, with independent teams, in view of observing the variability of modal properties of a built-up structure (related to specimen, measurement means, identification methodology)
- Organization of a numerical benchmark in condition of a study performed by a design office, in view of observing the total numerical variability of a dynamic simulation
- Application of methods tested on academic structures to complex industrial large number of degree of freedom structures
- Improvement of the modeling at macro-level of bolted structure assemblies
- Taking into account the environment, represented by complex boundary conditions
- Model improvement by adaptation and comparison of numerical-experimental correlation methods
- Numerical estimation of the model form uncertainty, and not only the parametrical uncertainty
- Improvement of the model robustness relative to uncertainties
- Confrontation of observed and numerical variabilities, and elaboration of recommendations for the use of numerical methods to a priori estimate the confidence of simulation-based predictions
- Establishment of empirical laws to a priori estimate the credibility related to a dynamic simulation result

16.5 Benchmarks Purpose (Parts 2 and 3)

The benchmark purpose is clearly to observe, from an *industrial* point of view, that is in the real conditions of an engineering study, the variability of computational blind and experimental modal results. The general Verification and Validation (V&V) comprehensive methodology based on benchmarks described in [4] can be kept in mind and successfully applied within the purpose of the observation of the numerical or experimental variability: a step-by-step procedure from the free-free separate components to the built-up system with complex boundary conditions is so here applied.

The dynamical systems of interest used for the benchmarking operations have been determined more and more the complexity of both the system and the boundary conditions, following the hierarchical process presented in Fig. 16.3:

- The eight free-free pump components;
- A two-component sub-assembly (Fig. 16.4a);
- The clamped pump assembly, not connected to pipes;
- The clamped pump assembly, connected to pipes (Fig. 16.4b).

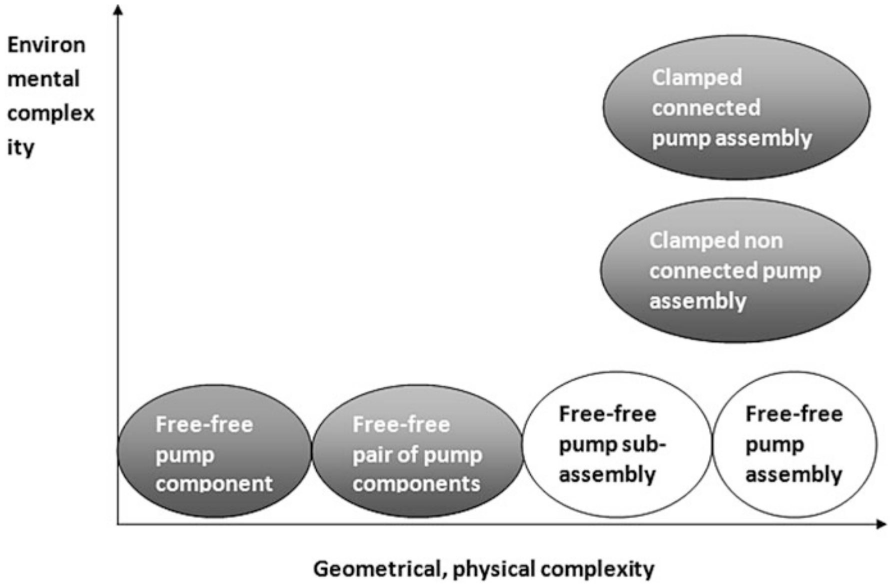

Fig. 16.3 The hierarchical procedure

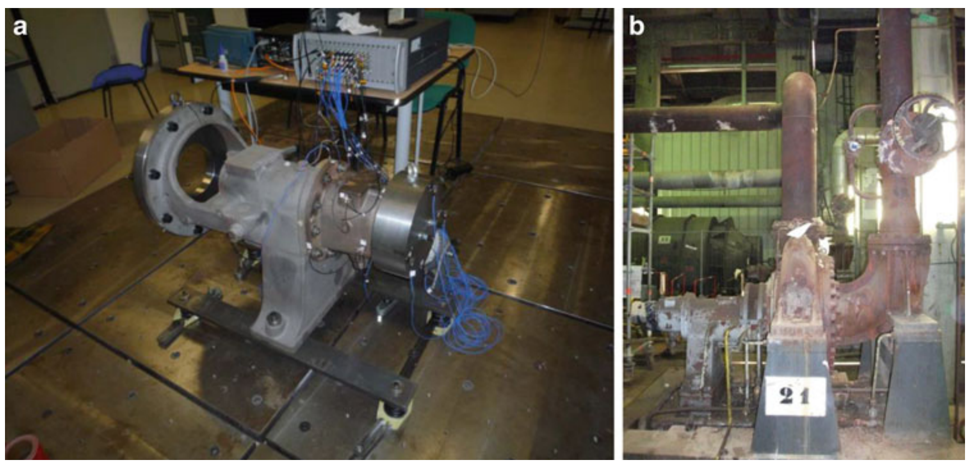

Fig. 16.4 The two-component assembly tested in laboratory and the pump in its industrial environment. (**a**) The two-component sub-assembly. (**b**) The pump, frame in concrete, connected to pipes, in thermical power plant

For each dynamical system, the modal basis on the bandwidth [0 Hz; 300 Hz] must be determined.

The number of independent blind simulated predictions and measurements are given in Table 16.1. Complementary simulations and corresponding experimental analyses have been performed by one partner only on a free-free pump sub-assembly and on the free-free pump assembly.

Table 16.1 Number of independent benchmark simulated predictions and measurements

	Number of simulations	Number of measurements
Free-free pump components	8−10	0–1
Free-free pair of components	3	3
Free-free sub-assembly	1	1
Free-free pump assembly	1	1
Non connected clamped pump assembly	10	2
Connected pump assembly	7	5

16.5.1 Numerical Benchmarks

The numerical benchmarks have been organized in the framework of 2008–2010 international SICODYN benchmark [1, 2] and Part 3 of 2012–2016 SICODYN project. The industrial point of view is taken into account by the fact that (1) here input benchmark data are not equally determined for all the partners, in order to consider their inherent uncertainty (data provided by EDF are but paper plans of the assembled pump and its parts, and CAD models of the eight main pump components) (2) the chosen demonstrator is an industrial structure in use in EDF thermal units: it is well-representative of modeling and boundary conditions complexity; (3) reference experimental data have been partially obtained in situ. Concerning benchmark data, material characteristic values are chosen by partners. Representation of pump components, boundary conditions and connections between components is let free choice.

This original benchmark approach, described in [1, 2, 12], is well adapted to the questions an industrial company must answer and critical decisions it must take: what is the confidence level of the simulation-based predictions provided by design offices? Are they sufficiently robust to uncertainties to authorize the cancellation or the decrease of experimental tests which characterize the dynamical behavior?

16.5.2 Experimental Benchmarks

The experimental modal analysis campaigns have been performed in the framework of 2008–2010 international SICODYN benchmark [1, 2] and Part 2 of 2012–2016 SICODYN project. The configurations of interest are the following:

- shaft and impeller system, bearing support and pump casing in free-free conditions;
- bearing support and bearing casing system in free-free conditions (three experimental modal bases);
- shaft, bearing support, cooling flange and bearing casing sub-assembly in free-free conditions (one experimental modal basis);
- pump assembly in free-free conditions (one experimental modal basis);
- non rotating in situ non connected pump assembly, frame fixed in concrete (two experimental modal bases relative to two specimens);
- non rotating in situ pump assembly, connected to delivery and suction pipes, frame fixed in concrete (two experimental modal bases on one specimen, three experimental modal bases on another specimen).

As for numerical benchmarks, no precise instructions on the number of sensors, the excitation type or the identification methods to be used are given to the partners. The observed experimental variability so attached to measurement “reference” data is to be considered during test-analysis correlation.

16.6 Quantification of the Numerical Uncertainties (Part 5)

Besides the observation of variabilities thanks to benchmarking operations, a priori quantification of numerical uncertainties is performed using methods able to represent the observed level of uncertainties. Methods to do so must be able to address both parametrical and model-form uncertainties. Model-form uncertainty originates from assumptions or simplifications of known, or unknown, phenomena that must be represented in the numerical simulation. Some of the modeling assumptions that influence simulation results in structural dynamics include the use of 1D, 2D, or 3D representation to model a component of the structure, the method through which contact and boundary conditions are represented. Thus, attempt to quantify the effect of model-form uncertainty and, as a consequence, the total numerical uncertainty have been far less encountered [13]. The methods to quantify the total numerical uncertainty, applied on the pump assembly, are (1) the generalized probabilistic approach, including both the model-parameter uncertainties and the model form uncertainties in a separate way [14], (2) the lack of knowledge theory [15], which is based on intervals whose bounds are probabilistic, and (3) the combined use of the component mode synthesis and the probabilistic uncertainty analysis [10]. The comprehensive approach, that is application of these methods to a complex industrial dynamical system with large uncertainties, and confrontation of so estimated uncertainties with the observed variability, is a main challenge of the SICODYN project.

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