Reliability Engineering and System Safety 96 (2011) 391–397

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Sensitivity analysis for reliable design verification of nuclear turbosets

Irmela Zentner [a,b,*], Stefano Tarantola [c], E. de Rocquigny [d]

[a] Lamsid—Laboratory for Mechanics of Aging Industrial Structures, UMR CNRS/EDF, 1, avenue Du Général de Gaulle, 92141 Clamart, France
[b] EDF R&D—Structural Mechanics and Acoustics Department, 1, avenue Du Général de Gaulle, 92141 Clamart, France
[c] Joint Research Centre of the European Commission—Institute for Protection and Security of the Citizen, T.P. 361, 21027 Ispra, Italy
[d] Ecole Centrale Paris—Applied Mathematics & Systems Department (MAS), Grande Voie des Vignes, 92 295 Châtenay-Malabry, France

ARTICLE INFO

Article history:
Received 24 February 2010
Received in revised form
11 October 2010
Accepted 22 October 2010
Available online 4 November 2010

Keywords:
Sensitivity analysis
Epistemic uncertainty
Turboset
Design verification

ABSTRACT

In this paper, we present an application of sensitivity analysis for design verification of nuclear turbosets. Before the acquisition of a turbogenerator, energy power operators perform independent design assessment in order to assure safe operating conditions of the new machine in its environment. Variables of interest are related to the vibration behaviour of the machine: its eigenfrequencies and dynamic sensitivity to unbalance. In the framework of design verification, epistemic uncertainties are preponderant. This lack of knowledge is due to inexistent or imprecise information about the design as well as to interaction of the rotating machinery with supporting and sub-structures. Sensitivity analysis enables the analyst to rank sources of uncertainty with respect to their importance and, possibly, to screen out insignificant sources of uncertainty. Further studies, if necessary, can then focus on predominant parameters. In particular, the constructor can be asked for detailed information only about the most significant parameters.

1. Introduction

Design verification is an essential step in the safe and reliable operation of large industrial structures, particularly when dealing with large and hazardous structures. This is generally undertaken through independent design assessment in order to make sure that the new machinery would operate safely and reliably. As it occurs before the acquisition of the assets, there is unavoidable lack of detailed information; moreover, the construction of a detailed mathematical model of the machine accounting for interaction with its operational environment is not feasible at this stage. As in other fields of structural design and safety, design verification engineering involves the consideration of uncertainty: among the large and heterogeneous sets of parameters lacking detailed information, it is typically useful to identify the most important contributors to exceedance of appropriate design criteria in order to focus additional information retrieval onto the critical model parameters, or, if necessary, change the design. Design verification should hence benefit from the large amount of on-going research devoted to developing uncertainty and sensitivity analysis within large industrial engineering and modelling [1–4].

The peculiar application motivating for this paper comes from the key case of design verification for nuclear turbosets. Before the acquisition of a turbogenerator, a key asset performs studies in order to verify that vibration levels remain in an acceptable range. But engineers lack the detailed information on the design of the new turboset. Uncertainties related to some model parameters could push the global behaviour of the turbogenerator into a critical zone, while other parameters have almost no influence on its dynamical behaviour.

For vibration diagnostic purposes, when rotating machinery have been installed, then models are quite detailed and the behaviour is generally identified by experimental tests. This is the context generally treated in the literature [5–7], where other sources of uncertainty, such as those related to unbalance, rotor misalignment and bearing clearances have to be accounted for. Some of these authors perform local sensitivity analysis (based on derivatives) for these models, for example, Petrov [7] and Chouchane et al. [8]. This approach is naturally limited as (i) it does not permit accounting for simultaneous variation of uncertain parameters and (ii) it is carried out with respect to a reference situation, although it is known that parameters interactions are generally important in dynamical problems as the one considered. Clearly, global sensitivity analysis is more appropriate for studying importance of model parameters in such complex dynamical systems.

The objective of this paper is therefore to propose a modus operandi for design verification that allows one to take into account epistemic uncertainty in the preliminary models. This procedure, based on global sensitivity analysis, is rooted in the common conceptual framework for quantitative uncertainty management in industrial applications introduced by de Rocquigny et al. [1].

---

* Corresponding author at: Lamsid—Laboratory for Mechanics of Aging Industrial Structures, UMR CNRS/EDF, 1, avenue Du Général de Gaulle, 92141 Clamart, France
E-mail addresses: irmela.zentner@edf.fr, izentner@yahoo.de (I. Zentner).

0951-8320/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ress.2010.10.005

In the phase of design verification, after the bid offer, and before installing the machines in the machine hall, relatively simple mechanical models are considered. At this stage, uncertainty is principally due to lack of knowledge and thus of epistemic nature. This means that model output variability could be reduced by collecting appropriate additional information. Supplementary information could be introduced by questioning the manufacturer on a limited number of elements or by enhancing some aspects of the rather simple finite element models used in the verification phase. This is the rationale for undertaking global sensitivity analysis.

Beyond that, there is generally a design criteria to verify in the context of design verification and thus there exits a threshold not to be exceeded by the model output or variable of interest. Therefore it seems interesting to complete the variance-based sensitivity analysis (implemented via the extended Fourier Amplitude Sensitivity Test [23]) by an importance measure accounting for the presence of the threshold. We have chosen Monte Carlo filtering along with the Smirnov statistics [2] in order gain complementary insights into the model behaviour. Other variance-based and non-variance-based sensitivity measures, providing useful complementary information to decision makers, are discussed in [9]. But, given the presence of the design criteria, Monte Carlo filtering seems the most appropriate technique in order to tackle this issue.

Note that several alternative methods have been suggested in the literature for treating epistemic uncertainty, the latter include probabilistic and extra-probabilistic approaches, see for example [10]. In this paper, uncertainty will be modelled in a probabilistic setting.

This is firstly because design verification requires communicable, easily-graspable and unequivoque procedures for decision-making, whereby a probabilistic setting encoding uncertainty with respect to observable quantities is an appropriate choice (cf. [1,10]). This approach is also convenient given the availability of both a "best-estimate" model, established by experienced engineers, and recognised information on the distribution of the input parameters. The information on the distributions of uncertainty in the inputs are related to their mathematical and physical properties in similar cases already tackled by established literature (e.g. [15]). Stiffness, for instance, is a positive variable and its inverse has to be finite. The stiffness of a spring might take values in the range $[k_{min}, \infty[$ where k_{min} is given by expert judgement while no upper value can be assigned. Indeed, with increasing stiffness, the spring tends to a fixed boundary condition (clamped), a possible but unlikely configuration. Besides, the parameters of the "best-estimate" model are generally interpreted as the mean or median values. Jaynes' maximum entropy principle [11] allows us then to assign "objective" probability distributions based only on available information.

The remainder of this paper is organised as follows. In Section 2, we give an overview over the study case and the probabilistic setting. We give a description of the deterministic "best-estimate" model used for turboset verification introducing variables of interest and design criteria. The topic of uncertainty quantification and modelling is also treated. In Section 3, the use of sensitivity analysis for design verification is addressed. We show how the uncertainty and sensitivity analysis are carried out in order to support decision-making in the design verification procedure.

2. Description of the study case: turboset model

This methodology developed in this paper is rooted in the common conceptual framework for quantitative uncertainty management introduced by de Rocquigny et al. [1]. The summary of the study characteristics is given in Table 1.

These study characteristics are detailed in the following sections.

2.1. Best-estimate model

We consider here a 1300 MW turbogenerator that is composed of one high-pressure (HP) and three low-pressure (BP) turbine cylinders as well as an alternator (ALT). The shaftline rests on 7 bearings (P1–P7) (see scheme in Fig. 1). The numerical model is a finite element model consisting of 1D-beam elements of varying diameter. Different diameters have been assigned to mass and stiffness elements in order to correctly represent the inertia and stiffness contribution of the bladed rotor rows [12]. Linear coefficients are used to represent the damping and the stiffness introduced by the oil film bearings in the system.

Likewise, the supporting structure (pedestal TG) is modelled by discrete elements (shown in Fig. 2) to which equivalent mass, stiffness and damping values are assigned. One of the most common techniques consists in converting the identified

Table 1
General setting of the problem.

Final goal of the uncertainty study	• Compliance with a threshold • Account for epistemic uncertainty • Better understanding of the model behaviour by the engineer (confirm expert judgment)
Variables of interest	M: sensitivity to unbalance parameter (depends on modal damping and eigenfrequencies)
Quantity of interest	Percentiles, probability of exceeding a given threshold
Decision criterion	Threshold not to be exceeded by the variable of interest (sensitivity to unbalance parameter)
Pre-existing/system model	Finite element model of the turbogenerator
Uncertainty setting	Probabilistic setting (epistemic uncertainty during design phase)
Model inputs (or factors) and uncertainty model developed	• Mechanical properties such as mass, stiffness, damping and rotation velocity: 20–25 uncertain model inputs • Probability distributions chosen from maximum entropy principle: gamma distribution (stiffness, damping) and uniform (others) • Parameters of distributions elicited through experience feedback and expert judgment
Propagation method(s) chosen	FAST, Quasi-Monte Carlo
Sensitivity analysis method(s) chosen	Morris method ("screening"), variance-based sensitivity indices and MC filtering along with Smirnov test statistic
Feedback process	If design criterion not met, *collect* more information on critical parameters in order to reduce uncertainty. Optionally change design