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An info-gap application to robust design of a prestressed space structure under epistemic uncertainties

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ABSTRACT

Uncertainty quantification is an integral part of the model validation process and is important to take into account during the design of mechanical systems. Sources of uncertainty are diverse but generally fall into two categories: *aleatory* due to random process and *epistemic* resulting from a lack of knowledge. This work focuses on the behavior of solar arrays in their stowed configuration. To avoid impacts during launch, snubbers are used to prestress the panels. Since the mechanical properties of the snubbers and the associated preload configurations are difficult to characterize precisely, an *info-gap* approach is proposed to investigate the influence of such uncertainties on design configurations obtained for different values of safety factors. This eventually allows to revise the typical values of these factors and to reevaluate them with respect to a targeted robustness level. The proposed methodology is illustrated using a simplified finite element model of a solar array.

1. Introduction

In the field of structural dynamics, the mathematical model depicting a real mechanical system must not only be validated against available test data, but also with respect to its final performance in the presence of uncertainties. Indeed, the required performance may be drastically affected even by a small perturbation of the design hypotheses such as the nominal model properties. Moreover, real environmental conditions and loads acting on a structure are usually unknown and are generally not accurately reproduced during tests. It is thus necessary to take these uncertainties into account in the design process.

This work focuses on the robust design of prestressed space structures such as solar arrays encountered on satellites (Fig. 1). During the spacecraft launch phase these are stowed in their folded configuration to save space under the launch vehicle fairing to reduce the risk of damage. Solithane snubbers (*i.e.* shock absorbers) are inserted between two adjacent panels to introduce a prestress and to absorb vibrations. However, under high excitation loads, a loss of contact may occur resulting in impacts which may damage both solar generators and fragile on-board equipment [1]. In practice, the specific load configuration for which the separation of two neighboring panels occurs is difficult to determine precisely since the exact level of prestress applied to the structure is uncertain.

Several classifications for the sources and types of uncertainties encountered in mechanical design problems can be found in the literature (*e.g.* in [2,3]). It is common in structural dynamics to distinguish two classes of uncertainties. The first one,

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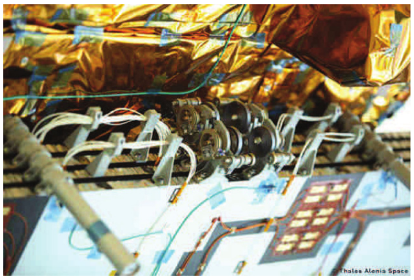
(a) Opening test



(b) Complex connexions between panels

Fig. 1. Views of solar generators on satellites.

called aleatory uncertainties, is due to the intrinsic randomness of the structure parameters such as the variability of its physical properties (*e.g.* Young's moduli, densities,...), of the manufacturing and assembling processes, of its service conditions (*e.g.* temperature, hydrometry,...), but also the variability of the experimental measuring process. The second class pertains to epistemic uncertainties. These result from a lack of knowledge or erroneous assumptions such as unknown values of junction equivalent stiffnesses, simplifying linearity hypothesis, omission of nonlinear or contact elements, unknown probability distributions of properties,...

It is common practice to use probabilistic methodologies [4] to quantify and to propagate aleatory uncertainties through the system model. A classical approach consists in using a deterministic finite element model and further adding uncertainties through either parametric or non-parametric methods. In parametric methods, the uncertain physical parameters are characterized by their mean value, their standard deviation or by probability density functions (*e.g.* Gaussian or uniform distributions). In non-parametric methods, model uncertainties are handled by directly introducing the uncertainties via global randomized matrices through dispersion parameters [5].

However, probabilistic approaches are not necessarily appropriate to treat all kinds of uncertainty. This is particularly true for epistemic uncertainties where the important information is simply missing. Non-probabilistic methods have thus been proposed including, for example, interval analysis [6,7], fuzzy sets theory [8,9] or lack-of-knowledge theory [10]. Ben-Haim initially proposed in [11] an approach dedicated to problems subjected to sever uncertainties, referred to as the *info-gap* theory: its basic concept consists in investigating the degree of lack of knowledge that can be tolerated while still satisfying a given critical level of performance.

This paper proposes to investigate the case of epistemic uncertainties due to lack of knowledge in the prestress level using an *info-gap* approach, in order to determine a robust design for solar arrays in their stowed configuration. The remainder of this article is organized as follows. In Section 2, a simplified finite element model of a solar array system is presented and its dynamic behavior is described. In Section 3, the general framework of an *info-gap* analysis is given and each of the associated components is further detailed within the scope of the previously described design problem. Finally, based on the derived indicators, the robustness of different design configurations is compared and the impact of the applied safety factor is investigated.

2. Simplified model of solar array system

As mentioned in the introduction, during the launch phase, spacecraft are subjected to a harsh dynamic environment. When large solar arrays are in their stowed configuration, impacts are thus likely to occur between two adjacent panels. In order to limit such phenomena and to avoid any resulting damage, dedicated snubbers are usually inserted between the panels, leading to the following modifications: firstly, an increase of the local stiffness, thus limiting the relative displacements; secondly, an induced prestress force, ensuring that contact is maintained between both panels. However, for high input levels, loss of contact between the snubbers and the panels may arise and impacts may still occur.

2.1. Finite element model

A finite element model of a simplified solar array has been developed in MSC-NASTRAN to investigate this problem, as depicted in Fig. 2. It consists in two plates (perpendicular to the z direction), meshed with 3072 elements (CQUAD4). The three stacking points are modeled using beam elements (CBEAM) that are linked to the plates through rigid body elements (RBE2). While neglecting the mass of these junctions, the masses associated with both upper hinges are taken into account using concentrated mass elements (CONM2), also linked to the plates by rigid body elements.

The associated element properties are given in Table 1, where $E,\ \rho,\ \nu,\ T,\ d$ and m represent the Young's modulus, the Poisson's ratio coefficient, the plate thickness, the beam cross section and the concentrated mass values, respectively. Finally, the snubbers' dynamic behavior is modeled by two linear springs inserted between points 1–2 and 3–4, acting along the global z-direction and whose stiffness values are initially equal to $k_s = 1 \times 10^5\ \mathrm{N\,m^{-1}}$.