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Nonlinear system identification in structural dynamics: 10 more years of progress

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ABSTRACT

Nonlinear system identification is a vast research field, today attracting a great deal of attention in the structural dynamics community. Ten years ago, an MSSP paper reviewing the progress achieved until then [1] concluded that the identification of simple continuous structures with localised nonlinearities was within reach. The past decade witnessed a shift in emphasis, accommodating the growing industrial need for a first generation of tools capable of addressing complex nonlinearities in larger-scale structures. The objective of the present paper is to survey the key developments which arose in the field since 2006, and to illustrate state-of-the-art techniques using a real-world satellite structure. Finally, a broader perspective to nonlinear system identification is provided by discussing the central role played by experimental models in the design cycle of engineering structures.

1. Introduction

To address the demand for structures and devices with ever-increasing technological and environmental performances, researchers in academia try more and more regularly to take advantage of nonlinear phenomena to outperform linear designs. For instance, Ref. [2] demonstrated a new mechanism for tunable rectification that uses bifurcations and chaos. In Ref. [3], a new strategy for engineering low-frequency noise oscillators was developed through the coupling of modes in internal resonance conditions. Another example is the cascade of parametric resonances proposed by Strachan et al. as a basis for the development of passive frequency dividers [4]. Nonlinearity is also increasingly exploited for vibration absorption [5–7] and energy harvesting [8–10].

If attempts to utilise nonlinearity are today frequent in the technical literature, current designs and models in industry predominantly remain linear. However, nonlinearity is often encountered during the tests performed on the first prototype of a structure. In addition to distorted resonances and jumps between high- and low-amplitude responses, nonlinearity can generate complex dynamic phenomena, such as subharmonic and superharmonic resonances, modal interactions, quasi-periodicity and chaos, with the consequence that essentially-linear models may fail to predict the structural response within the necessary level of reliability [11].

Two examples taken from the aerospace sector and for which nonlinearities were detected during ground vibration test campaigns are the Cassini–Huygens spacecraft [12] and the Airbus A400M aircraft [13]. In the former example, distorted

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frequency responses and jump phenomena around a critical mode were reported. Because this nonlinear behaviour was an important concern as for the integrity of the spacecraft, additional tests were conducted, and revealed that nonlinearity was caused by the appearance of gaps in the support of the Huygens probe. In the latter example, structural resonances showing significant peak skewness were incorrectly fitted by a linear modal analysis software. Different sources of nonlinearity, including elastomeric mounts and hydraulic actuators, were ascertained after careful analysis. As evidenced by these two examples, nonlinear phenomena complicate vibration test campaigns, and usually require profound investigations for which nonlinearity must first be identified.

The present paper was preceded by a number of other literature overviews. In 1998 and 2000, the developments conducted until the end of the 20th century were reviewed by Adams and Allemang [14] and Worden [15], respectively. The first book on nonlinear system identification in structural dynamics was published a couple of years later [16]. In 2006, a great many existing methods to tackle nonlinearity detection, characterisation and parameter estimation were surveyed [1]. The need for this new review paper arises from the progress made during the last 10 years, which substantially advanced the available capabilities in the identification of nonlinear mechanical systems. Specifically, even if there are still significant challenges ahead of us, the first methods that can potentially address large-scale structures vibrating in strongly nonlinear regimes were developed. In addition, researchers recognised the importance of quantifying uncertainties in nonlinear system identification, which led to a change of paradigm within the community.

The paper starts in Section 2 with a discussion on the factors which have driven the recent progress achieved in nonlinear system identification in structural dynamics. It is explained that advances in nonlinear theory, computation and testing have largely contributed to this progress. In Section 3, a review of the key developments which arose during the 2006–2016 decade is conducted. The main focus of this literature survey is on parameter estimation methods, classified into seven categories as suggested in Ref. [1], namely linearisation, time- and frequency-domain methods, time–frequency analysis, modal methods, black-box modelling and numerical model updating. A number of state-of-the-art methods are illustrated in Section 4 using experimental data measured on a real-world satellite structure. In a second part, this section goes beyond nonlinear system identification, and highlights the central role played by experimental models in the design cycle of engineering structures. Finally, concluding remarks are drawn in Section 5 and directions for future research are suggested.

2. A perspective on the global progress in nonlinear mechanical vibrations

Two facts have arguably acted as catalysts for the progress across the nonlinear system identification field. First, nonlinearity manifestations have been increasingly encountered by engineers during vibration tests [11]. For instance, the linear modal analysis of two aircraft of the Airbus family, namely the A400M and the A350XWB, was experimentally confronted with nonlinearities in elastomeric engine mounts and hydraulic actuators [13], in landing gears [17] and in the auxiliary power unit of the airframe tail-cone [18]. Second, the pressure faced in industry to devise environment-friendly structures has greatly escalated. As an illustration, the report of the *High Level Group on Aviation Research in Europe* [19] deems necessary to achieve by 2050 reductions of 75% in CO_2 emission and 90% in NO_x emission per passenger kilometre. This ambitious goal necessarily entails the design of lighter aircraft structures featuring new technologies, e.g., composite materials, which inevitably makes nonlinear behaviours more significant [20].

These two facts have motivated researchers in academia to make the first attempts to apply nonlinear system identification to real structures. These contributions mostly feature ad hoc approaches derived to solve specific nonlinearity modelling problems. As examples, experimental modal analysis of an engine casing assembly and nonlinear finite element model updating of a complete aircraft engine model were carried out in Refs. [21] and [22], respectively. The nonlinearities of structural prototypes of full-scale satellites were identified in Refs. [23,24] based on typical qualification test campaign data. Ref. [25] estimated the variation of the natural frequencies and damping ratios of an Agusta-Westland helicopter as a function of the response level. The performance of nonlinear devices embedded in large structures was also examined, as in Ref. [26], where a nonlinear vibration absorber was used to mitigate the high response levels of an eleven-ton, nine-storey building subject to blast events.

Adopting a wider perspective, important advances have been achieved since the beginning of the 2000s in the three facets of the analysis of nonlinear mechanical vibrations, namely theory, computation and testing. We provide in what follows a brief review of this global progress, which has clearly contributed to push the envelope in nonlinear system identification.

2.1. Theory

The theory of nonlinear dynamic systems was developed by pure mathematicians based on the seminal work of Poincaré. A couple of decades ago, this theory spread across the engineering field thanks to a series of reference monographs, thoroughly characterising the different phenomena and attractors nonlinear mechanical systems can exhibit. Nayfeh and Mook [27] applied perturbation methods to study nonlinear phenomena in single- and multi-degree-of-freedom systems. Guckenheimer and Holmes [28] adopted a different, geometric viewpoint, appearing as an ideal companion to the perturbation approach, and Kuznetsov [29] published a complete treatise on bifurcations. It is only recently that theories

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