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Complex dynamics of a nonlinear aerospace structure: Experimental identification and modal interactions

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A B S T R A C T

Nonlinear system identification is a challenging task in view of the complexity and wide variety of nonlinear phenomena. The present paper addresses the identification of a real-life aerospace structure possessing a strongly nonlinear component with multiple mechanical stops. The complete identification procedure, from nonlinearity detection and characterization to parameter estimation, is carried out based upon experimental data. The combined use of various analysis techniques, such as the wavelet transform and the restoring force surface method, brings different perspectives to the dynamics. Specifically, the structure is shown to exhibit particularly interesting nonlinear behaviors, including jumps, modal interactions, force relaxation and chattering during impacts on the mechanical stops.

1. Introduction

System identification in structural dynamics, which aims at building accurate mathematical models from input and output measurements acquired on the real structure, is a discipline that has evolved considerably during the last few decades. Since the early eighties, modal analysis [1,2], which is indubitably the most popular approach to performing linear system identification of vibrating structures, has successfully embraced increasingly complex systems in a broad range of application fields. It is fair to say that modal analysis is today a mature research area, which is routinely practiced in industry using advanced and sophisticated techniques [3,4]. However, with the continual interest in expanding the performance envelope of engineering systems, the utilization of nonlinear components is becoming more and more frequent. There thus exists a need for the development of effective system identification techniques applicable to nonlinear systems.

Nonlinear system identification is a challenging task in view of the complexity and wide variety of nonlinear phenomena. A significant progress has been enjoyed during the last 15 years or so [5] and, to date, multi-degree-of-freedom lumped-parameter systems and continuous structures with localized nonlinearities are within reach [6–9]. The identification of weak nonlinearities in more complex systems was also addressed in the recent past. In particular, Platten et al. successfully applied the so-called nonlinear resonance decay method [10] to an aircraft-like experimental structure that consists of a wing with two stores suspended by means of nonlinear pylons with hardening characteristics [11]. A variant of the nonlinear resonance decay method combined with a direct parameter estimation technique [12] was also proposed in [13], and provided good results in the nonlinear identification of the aileron mode of a large transport aircraft. Another

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methodology, limited in principle to weakly nonlinear behavior and based on frequency response measurements, was introduced by Carrella and Ewins [14], where data collected on a complete helicopter revealed a marked softening of one vibration mode of the structure.

The identification of large-scale structures with multiple, and possibly strongly, nonlinear components nevertheless remains a distinct challenge and concentrates current research efforts. In this context, nonparametric approaches, whereby no a priori assumption is made regarding the type and the strength of the nonlinearities, are frequently adopted. For instance, it was lately shown that the equivalence between analytical and empirical slow flows yields an identification methodology applicable to a large class of nonlinear systems [15]. This was confirmed numerically using a rigid-wing model with aeroelastic nonlinearity [16], and experimentally on a bolted beam assembly exhibiting nonlinear friction effects [17]. The nonlinear modal properties of a similar set-up were also studied in [18], applying nonparametric techniques to measurements recorded using a scanning laser Doppler vibrometer. An interesting alternative to nonparametric modeling is the recourse to parametric models, which are generally sought by the practicing engineer because of their link with the physics. This is why the present paper addresses the parametric identification of the SmallSat spacecraft developed by EADS-Astrium, and possessing a vibration isolation device with multiple mechanical stops.

The contribution of the paper stems from an unconventional application of established and robust analysis techniques to identify this large-scale, strongly nonlinear structure. The complete identification procedure, from nonlinearity detection and characterization to parameter estimation [5], will be achieved based upon experimental data collected during a classical spacecraft qualification campaign. Because such campaigns are constrained by the need to reduce the measurement time, no dedicated tests were performed for the purpose of this study. Typical sine-sweep driven-base data will therefore be exploited without the knowledge of the actual input force at the shaker-to-structure interface.

Throughout the paper, the combined use of analysis techniques will bring different perspectives to the dynamics. Specifically, the spacecraft will be shown to exhibit particularly interesting nonlinear behaviors, including jumps, modal interactions, force relaxation and chattering during impacts on the mechanical stops. A specific attention will be devoted to nonlinear modal interactions as their experimental evidence in the case of a complex, real-life structure is another important contribution of this work. In particular, it will be found that – potentially dangerous – nonlinear resonances between modes with noncommensurate linear frequencies are possible due to the frequency–energy dependence of nonlinear dynamics. These observations will be compared with numerical predictions obtained by applying continuation algorithms to a finite element model of the satellite structure.

The present paper starts with a detailed introduction to the SmallSat structure and its nonlinear vibration isolation device in Section 2. Low-level random data are exploited using a subspace algorithm applied to transmissibility functions to estimate the linear modal properties of the spacecraft. Nonlinearity detection is achieved in Section 3 through the visual inspection of the raw sine-sweep time series and phase-plane portraits. Restoring force plots and time-frequency spectra are then analyzed in Section 4 to gain additional insight toward accurately characterizing nonlinear behavior. Finally, a multi-degree-of-freedom formulation of the restoring force surface method, first introduced by Masri and Caughey [19], will be established in Section 5 to estimate the parameters of the nonlinear device.

2. The SmallSat spacecraft structure

The SmallSat structure was conceived by EADS-Astrium as a low-cost platform for small satellites in low earth orbits [20]. It is a monocoque tube structure which is 1.2 m in height and 1 m in width. It is composed of eight flat faces for equipment mounting purposes, creating an octagon shape, as shown in Fig. 1. The octagon is manufactured using carbon-fiber-reinforced plastic by means of a filament winding process. The structure thickness is 4 mm with an additional 0.25 mm-thick skin of Kevlar applied to both the inside and outside surfaces to provide protection against debris. The top floor is a 1 m^2 sandwich aluminum panel, with 25 mm core and 1 mm skins. The interface between the spacecraft and the launch vehicle is achieved via four aluminum brackets located around cut-outs at the base of the structure. The total mass including the interface brackets is around 64 kg.

The spacecraft structure supports a dummy telescope mounted on a baseplate through a tripod; its mass is around 140 kg. The dummy telescope plate is connected to the SmallSat top floor by three shock attenuators, termed shock attenuation systems for spacecraft and adaptor (SASSAs) [21], whose dynamic behavior may exhibit nonlinearity. Besides, as depicted in Fig. 2(a), a support bracket connects to one of the eight walls the so-called wheel elastomer mounting system (WEMS) device which is loaded with an 8 kg dummy inertia wheel. The WEMS device acts as a mechanical filter which mitigates high-frequency disturbances coming from the inertia wheel through the presence of a soft elastomeric interface between its mobile part, i.e. the inertia wheel and a supporting metallic cross, and its fixed part, i.e. the bracket and by extension the spacecraft. Moreover, the WEMS incorporates eight mechanical stops, covered with a thin layer of elastomer, and designed to limit the axial and lateral motions of the inertia wheel during launch, which gives rise to strongly nonlinear dynamic phenomena.

Fig. 2(b) presents a simplified, yet relevant, modeling of the WEMS device where the inertia wheel, owing to its important rigidity, is seen as a point mass. The four nonlinear connections (NCs) between the WEMS mobile and fixed parts are labeled NC 1–4. Each NC possesses a trilinear spring in the axial direction (elastomer in traction/compression plus two stops), a bilinear spring in the radial direction (elastomer in shear plus one stop), and a linear spring in the third direction (elastomer in shear). The stiffness and the damping properties of the WEMS were estimated during