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Nonlinear modal identification of a steel frame

J.L. Zapico-Valle [a],*, M. García-Diéguez [b], R. Alonso-Camblor [b]

[a] Department of Construction and Manufacturing Engineering, University of Oviedo, Campus de Gijón 7.1.16, 33203 Gijón, Spain
[b] Department of Construction and Manufacturing Engineering, University of Oviedo, Campus de Gijón 7.1.BC, 33203 Gijón, Spain

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ABSTRACT

The nonlinear modal identification of a four-storey steel frame is presented in this paper including both the experimental and the analytical aspects. The first two bending modes of the frame were experimentally isolated by a single-point mono-harmonic excitation. The subsequent free decay vibration was measured and used for identification purposes. An original filtering procedure was developed in order to overcome the drawbacks of the common band-pass filters and to enhance the accuracy of the signals. The nonparametric identification of the structure was carried out through an expeditious procedure based on the analysis of the evolution of the apparent frequency and equivalent viscous damping coefficient as a function of the apparent amplitude of the free decay cycles. The results of this identification reveal that the structure is weakly nonlinear in stiffness and strongly nonlinear in damping, while the mode shapes remain linear within the range of measurements. Asymptotic nonlinear laws defined in the modal space where proposed to model both the stiffness and the damping. This is another original contribution in this paper. The proposed nonlinear model was fitted to the experimental data in the time domain. Results were excellent with fitting errors three orders of magnitude lower than those of a pure linear model.

1. Introduction

Framed structures are extensively used in civil engineering applications such as buildings and industrial constructions. The design and further control and monitoring of these structures are commonly based on mathematical models, experiments and previous experiences. Linear models are usually used for analyzing these structures in the engineering applications. This approach strongly simplifies the modelling, analysis and extraction of modal properties. However, linearity seldom occurs in reality. Structures always contain some degree of nonlinearity due to material and interface behaviour, instabilities, etc. [1]. Therefore, an epistemic error is introduced by the linear modelling and a nonlinear approach should be used when more accurate predictions are required.

This is the case when evaluating the dynamic response of a structure at or near resonances. Under these conditions, the stiffness and inertial forces tend to cancel each other out and the response is governed mainly by damping. It is well known that damping is often amplitude dependent. For this reasons, damping measurements are recommended in Reference [2] as a way to achieve accurate damping models to check the vibration serviceability of footbridges. ISO code [3] also encourages the choice of a suitable damping model and its calibration through experiments to check the serviceability of buildings and walkways against vibrations. Advanced seismic design codes [4] include several performance criteria for steel framed structures. No significant damage to the structure is recommended for the immediate occupancy performance level. This means that the structure should remain in the elastic range during the seismic excitation. Under these circumstances, the structure response is also dominated by damping. Appropriate modelling and calibration of damping is thus essential for the verification of this performance level. These are just a few examples in which damping could be a significant design factor.

Due to safety as well as economic reasons, in many cases the performance of structures should be checked once they are set up. As the structures tend to degrade when aging, their integrity should also be monitored periodically or continuously. After an exceptional event such as an overload, earthquake, and hurricane structures may result damaged and an evaluation of their integrity should be carried out. All these engineering tasks are referred to as structural health monitoring (SHM) in literature. During the last decades, numerous SHM techniques based on the analysis of measured vibration response were developed. Reference [5] includes a comprehensive literature review of these techniques. In this survey it is conclude that even though the majority of the reviewed damage identification techniques rely on linear models fit to measured data, nonlinear identification techniques are potentially interesting due to the inherent nonlinear nature of the damage. More specifically, Brandon [6] states that nonlinear identification can provide

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* Corresponding author. Tel.: +34 985 18 19 28; fax: +34 985 18 20 55.
E-mail address: jzapico@uniovi.es (J.L. Zapico-Valle).

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valuable information for SHM. The author advocates the use of time-domain system identification techniques to retain important nonlinear information, which is lost when linearizing time series. Modena et al. [7] claim the use of damping and nonlinear responses as damage-sensitive features.

The theory of nonlinear systems is extremely broad and a large body of literature is available, as reported in References [1,8]. Many potential applications of the nonlinear theory in structural engineering are also highlighted in these references. This field has evolved and is a mature subject nowadays. Even though the literature on testing and identification of nonlinear structures is abundant, only few practical methods of modal testing have been established so far. Some recent publications in this area are outlined in the next paragraphs. Atkins et al. [9] propose an extension of the linear force appropriation method to the identification of weakly nonlinear structures. By an appropriate force choice, which includes high harmonic terms, the structure is made to respond in a single mode corresponding to the underlying linear structure. An optimization approach is chosen to determine the multi-harmonic components of the force vector. The restoring force surface method is used to identify the linear and nonlinear terms in the equation of motion of each individual mode. The nonlinear cross-coupling terms are separately identified. Platten et al. [10] developed a method for the identification of complex structures that are predominantly linear and feature a small number of nonlinear modes. They use an extension of the resonant decay method, in which appropriate burst sine forces are applied to excite single modes or small groups of coupled modes. The restoring force surface method is finally used to curve-fit the results in modal space obtaining thus the modal parameters of each mode. Peeters et al. [11,12] extended the phase resonance testing to nonlinear systems by using the nonlinear normal modes (NNMs) theory. In this method, underlying NNMs are individually excited instead of linear modes. This is achieved by tuning a multi-harmonic excitation such as the response is in quadrature with respect to the excitation. After this NNM force appropriation, the excitation is turned off and the subsequent free decay vibration, in which only the excited mode remains due to its invariance, is used to extract the modal curves and corresponding frequencies through time-frequency analysis. The aforementioned methods were applied to numerical simulations or to small experimental rigs. In these cases, the type of nonlinearity present in the structure, which constitutes the essential issue to be addressed in the identification process, is known beforehand. The applications of nonlinear modal identification to full-scale engineering structures with multiple components is scarce in literature, despite their potential usefulness.

This paper deals with the nonlinear modal identification of an experimental four-storey medium-size steel frame. A practical identification procedure to be applied to similar structures is sought in this study. Taking into account the highly individualistic nature of nonlinear systems [8], the main goal here is to discover the nonlinear features of the frame through dynamic experiments. From this knowledge, a suitable dynamic model, that can be easily implemented in the engineering applications, will be inferred. The model will be finally calibrated by fitting experimental data. The calibrated nonlinear model will be used for future applications on SHM, finite element model updating and structural serviceability checking. To achieved the planned objectives, a two-step experimental procedure similar to those of Refs. [9–12] is proposed. The isolation of single modes by appropriate harmonic excitation is sought in the first step. The subsequent free decay vibration is used for identification purposes. The multi-point multi-harmonic appropriation established in [9–12] is very popular in the aerospace industry. However, it is not practical for in-service civil engineering applications. Instead, an imperfect appropriation consisting in a single-point mono-harmonic excitation was chosen for this case. In Ref. [12], it is stated that this excitation isolates satisfactorily a nonlinear modal mode if the structure has well-separated modes. A novel procedure is tried to filter the raw digital signals. The procedure is aimed to keep most of the original nonlinear information, which can be removed when using conventional filters. The filtered signals are used for the nonparametric identification of the structure. There are some nonparametric identification methods available in literature. The method developed by Feldman [13] based on Hilbert transform constitute a prominent example. In the present case, a more expeditious procedure is developed in order to study the evolution of both the stiffness and damping as a function of the vibration amplitude and to infer appropriate models for them. The calibration of the proposed models is posed as the minimization of an error function defined in the time domain and accounting for the discrepancies between the response predicted by the model and the experiments. The model response is computed from the initial conditions through a finite differences scheme. An adaptive stochastic algorithm developed previously by the authors [14] is adopted for the minimization. This algorithm is very effective in solving nonlinear-in-the-parameters cases.

2. Experimental part

2.1. Structure

The Uniovi Structure is a middle-size four-storey steel frame with two bays in the longitudinal direction and one bay in transversal one. The overall dimensions of the structure are 4 m length, 1.5 m width and 7.3 m height (see Fig. 1). All columns and beams are HEA-120 and IPN-100, respectively, of steel grade S-275. The floors of the frame are 4 mm thick steel sheets connected to the beams through discontinuous welding. The foundations consist of two continuous concrete beams lying on the floor of the laboratory.

Each column consists of two pieces. They are spliced through end plates connected by four bolts 12 mm in diameter. The columns are welded to 20 mm thick plates anchored to the foundation. The beams corresponding to the transversal direction are directly connected to the web of columns by a welded-all-around fillet. In the longitudinal direction, however, the beams are connected to the

Fig. 1. Uniovi structure.