Mechanical Systems and Signal Processing 102 (2018) 401–430

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Integration of system identification and finite element modelling of nonlinear vibrating structures

Samson B. Cooper [*], Dario DiMaio, David J. Ewins

University of Bristol, Department of Mechanical Engineering, Queen's Building, University Walk, Bristol, United Kingdom

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 22 September 2017
Accepted 23 September 2017

Keywords:
Nonlinear identification
Finite element
Numerical simulation
System integration

ABSTRACT

The Finite Element Method (FEM), Experimental modal analysis (EMA) and other linear analysis techniques have been established as reliable tools for the dynamic analysis of engineering structures. They are often used to provide solutions to small and large structures and other variety of cases in structural dynamics, even those exhibiting a certain degree of nonlinearity. Unfortunately, when the nonlinear effects are substantial or the accuracy of the predicted response is of vital importance, a linear finite element model will generally prove to be unsatisfactory. As a result, the validated linear FE model requires further enhancement so that it can represent and predict the nonlinear behaviour exhibited by the structure. In this paper, a pragmatic approach to integrating test-based system identification and FE modelling of a nonlinear structure is presented. This integration is based on three different phases: the first phase involves the derivation of an Underlying Linear Model (ULM) of the structure, the second phase includes experiment-based nonlinear identification using measured time series and the third phase covers augmenting the linear FE model and experimental validation of the nonlinear FE model. The proposed case study is demonstrated on a twin cantilever beam assembly coupled with a flexible arch shaped beam. In this case, polynomial-type nonlinearities are identified and validated with force-controlled stepped-sine test data at several excitation levels.

1. Introduction

Nonlinearities often originate from different sources in engineering structures. A large majority of these nonlinearities are narrowed down to the design of the structure, the nature of the joints and material and geometric properties. Research on bolted joints and other types of nonlinear features have been found to introduce large uncertainties in the stiffness and damping properties of a structure which can often render the behaviour of the structure nonlinear. Identification and prediction of the effect of these nonlinearities at operational conditions is of current challenge to present structural engineers dealing with complex nonlinear structures. In this context, the effective integration of experimental nonlinear identification and FE modelling of engineering structures would be of great advantage to the present structural dynamic community.

Nonlinear system identification is important in many structural dynamic applications. Aside from the distorted resonances and jumps observed between high and low-amplitude responses, nonlinearity can generate complex dynamic behaviour such as modal interaction, subharmonic and super harmonic resonances, quasi-periodicity and chaos. For example, in complex aerospace and mechanical structures [1], micromechanical systems with magnetic or friction forces [2,3],

---

[*] Corresponding author.
E-mail address: sc14784@bristol.ac.uk (S.B. Cooper).

https://doi.org/10.1016/j.ymssp.2017.09.031
0888-3270/© 2017 Elsevier Ltd. All rights reserved.

machineries with rubber isolation mounts and assembled structures with bolted interfaces [4–6]. In most engineering designs, structures are often considered to behave linearly, but the vibration testing and operational performance of some of these structures exhibit some nonlinear phenomena which can no longer be ignored or assumed as linear [7]. Hence, the accurate representation of these nonlinear features in the finite element model of the structure would be of extreme benefit in obtaining better response prediction at the forcing range of interest.

1.1. Nonlinear system identification

In the last two decades, significant progress has been made in the experimental identification of nonlinear systems with the development of several nonlinear identification methods such as the Hilbert Transform (HT) approach [8–11], wavelet transform [1], the reverse path method [12,13], black-box modelling approach [14,15] and the most recent frequency-domain nonlinear subspace identification in [16]. Another common method used for identifying the stiffness and damping properties of a nonlinear structure is the Restoring Force Surface (RFS) method sometimes referred to as the Force State Mapping method developed by Masri and Caughey [17–19]. The RFS approach has been successfully applied to different structures and nonlinear experimental investigation such as [20–22]. For a full review on nonlinear identification methods, the reader is encouraged to read the review paper presented in [12] and its sequel in [23].

These nonlinear identification methods have not only been applied to theoretical and numerical simulations but have also been implemented experimentally on large-scale industrial structures. Examples of the industrial application of some of these nonlinear identification methods are also available in the literature where the identification of weak nonlinearities was studied on a more complex aerospace structure in [24] and a strategy for non-linear modal identification of weak nonlinear effects on a large aircraft was presented. A study was also carried out on a large helicopter with the identification of weak nonlinear softening behaviour on one of the vibration modes as shown in [25]. Further examples of case studies where nonlinearity has been identified in aerospace structures can be found in [26] where nonlinearity was also detected at the elastomeric mounts supporting the four turboprop engines of the aircraft during the Ground Vibration Test (GVT) of the Airbus A400M aircraft designed for military purposes. A F-16 fighter aircraft also showed some complex nonlinear behaviour at wing-to-payload mounting interface of the aircraft when a similar GVT was conducted [27]. Nonlinearity was also observed on the Cassini spacecraft due to the presence of gaps in the support of the Huygens probe [28]. These nonlinear identification methods are mainly used to characterise the types of nonlinearity i.e. (cubic, splines, polynomial, symmetric or asymmetric and either damping or stiffness-oriented nonlinearity) and also to obtain nonlinear parametric values present in the test structure. However, the results obtained from the experimental nonlinear identification are not often integrated into the FE models of the structure. Where the design of the structure can be exploited to understand the experimental measurement, uncover new nonlinear phenomena, make design modifications and also predominantly optimise the structural design process iteratively to obtain the most efficient design before final production.

1.2. Numerical computation

Different algorithms and numerical methods for the computation of nonlinear systems have been developed over the last 15 years, most of them are based on a continuation procedure [29] and are used for studying the periodic solution of a nonlinear system with respect to the frequency of the harmonic forcing or design parameter. Examples of these numerical methods includes the shooting method [30] which is based on Newmark time integration, orthogonal collocation methods such as COLSYS [31], AUTO [32], MATCONT [33] and most recently developed COCO [34], all of which are also useful for bifurcation detection and tracking. Another powerful numerical method in the frequency domain is the Harmonic Balance (HB) method. It is often used to compute the periodic solution of finite element models (FEM), with the main advantage on the use of truncated and low order Fourier approximations to obtain an accurate solution for a nonlinear system. The HB method has been applied to several mechanical and vibration problems, examples of these applications are found in the subsonic flow of an aerofoil motion with strong cubic nonlinear restoring force [35], unsteady aerodynamic prediction of helicopter rotors [36], modelling of friction interface elements [37] and the prediction of nonlinear dynamic response of mechanical structures [38,39].

1.3. Objectives of the paper

Despite many advances in nonlinear system identification and developments in the numerical computation of nonlinear systems, there is little or no activity on the integration of experimental nonlinear identification and the validation of FE models of structures with identified nonlinearities using measured and numerical data. In addition, engineers today most especially in the aerospace industry are now being confronted with the challenge of predicting the vibration response and validating FE models of structures with identified nonlinearities. To this end, the main contribution of the present paper is to present a practical application of the integration of nonlinearities in the design and development of structural models. The primary objective of the paper is to explore the potential and ability of obtaining a validated nonlinear FE finite model of a structure by implementing developed experimental techniques and numerical tools available in the proposed literature. This paper follow an earlier opinion paper in [7] where a new approach to modal testing was proposed for nonlinear structures. The entire approach consists of 10 different steps and was introduced for extending current modal testing technology