Mechanical Systems and Signal Processing 96 (2017) 139–158

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Excitation power quantities in phase resonance testing of nonlinear systems with phase-locked-loop excitation

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ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 7 April 2017
Accepted 9 April 2017
Available online 19 April 2017

Keywords:
Nonlinear normal modes
Phase resonance testing
Nonlinear mode indicator function
Phase-locked-loop
Nonlinear system identification

ABSTRACT

Phase resonance testing is one method for the experimental extraction of nonlinear normal modes. This paper proposes a novel method for nonlinear phase resonance testing. Firstly, the issue of appropriate excitation is approached on the basis of excitation power considerations. Therefore, power quantities known from nonlinear systems theory in electrical engineering are transferred to nonlinear structural dynamics applications. A new power-based nonlinear mode indicator function is derived, which is generally applicable, reliable and easy to implement in experiments. Secondly, the tuning of the excitation phase is automated by the use of a Phase-Locked-Loop controller. This method provides a very user-friendly and fast way for obtaining the backbone curve. Furthermore, the method allows to exploit specific advantages of phase control such as the robustness for lightly damped systems and the stabilization of unstable branches of the frequency response. The reduced tuning time for the excitation makes the commonly used free-decay measurements for the extraction of backbone curves unnecessary. Instead, steady-state measurements for every point of the curve are obtained. In conjunction with the new mode indicator function, the correlation of every measured point with the associated nonlinear normal mode of the underlying conservative system can be evaluated. Moreover, it is shown that the analysis of the excitation power helps to locate sources of inaccuracies in the force appropriation process. The method is illustrated by a numerical example and its functionality in experiments is demonstrated on a benchmark beam structure.

1. Introduction

Experimental modal analysis (EMA) is the most common procedure for the identification of linear dynamic structures. It provides a very user-friendly way of extracting comprehensive information about the dynamic properties of a system. However, its limitation to linear systems has become more and more substantial as the complexity of engineering structures grows and the demand for light-weight and efficient structures increases. Many of these requirements cannot be met without explicitly taking into account nonlinearity in the design process. This development poses new challenges for the numerical and the experimental analysis in structural dynamics.

On the experimental side this generates a need for reliable and easy to use nonlinear system identification techniques. Even though there are numerous techniques for nonlinear identification [1,2] many of them are limited to small scale systems, weak nonlinearity or are difficult to relate to a clear physical meaning [3]. Oftentimes, it is also required to investigate the linear structure separately from the nonlinearities which requires additional experimental effort.

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http://dx.doi.org/10.1016/j.ymssp.2017.04.011

A promising concept to overcome some of these drawbacks is the concept of nonlinear modes, which provides global information about the system's linear and nonlinear dynamics along with a clear physical meaning [4]. The concept was introduced in the 1960s by Rosenberg as an extension of linear normal modes (LNM) to nonlinear systems [5]. A nonlinear normal mode (NNM) according to Rosenberg's definition is a synchronous, periodic motion of a conservative system. This definition provides a clear theoretical framework and a direct relation to linear modes. An extension of the concept of nonlinear modes to non-conservative systems was provided by Shaw and Pierre in the 1990s [6] who showed that the nonlinear modal motion can be regarded as a motion on an invariant manifold in the phase space. Despite the generality of this definition and its valuable theoretical insights to nonlinear modal dynamics most practical applications still basically rely on Rosenberg's definition. This is partly due to the fact that there are powerful and reliable numerical algorithms like the shooting method [7] or the Harmonic Balance Method (HBM) [8] for the calculation of the periodic motions on a NNM branch. Moreover, nonlinear modal interactions can be resolved in a straightforward way by extending Rosenberg's definition to non-necessarily synchronous periodic motions as it has been done by Kerschen [4].

Generally, the modes of the underlying undamped system provide valuable insight into the dynamics of the damped system and the assessment of the undamped modes is therefore for linear systems common practice [9]. The first approach for nonlinear EMA, presented by Peeters [10], extended phase resonance testing to nonlinear structures, and also essentially relies on the definitions of Rosenberg and Kerschen for conservative nonlinear modes. More recent phase separation methods for nonlinear modal analysis [11] are based on the same framework. The efficient numerical algorithms for the calculation of NNMs furthermore provide a powerful tool for parameter estimation based on experimental data [12]. In this paper NNMs are defined according to Rosenberg's definition with the extension of Kerschen, such that internal resonances are generally taken into account, even though they are not the main focus of this work.

The phase resonance method, which was proposed by Peeters in 2010 [10] and subsequently proved its applicability in several experimental studies [10,13,14], poses some practical difficulties. In this approach the excitation frequency of a forced and damped system is varied manually until the NNM motion of the underlying conservative system is approximately isolated. This is a difficult and very time consuming procedure. Especially lightly damped systems, which are indeed the systems of interest in an NNM analysis, are very sensitive to changes of the excitation frequency near sharp resonance peaks of the frequency response. The increments of the excitation frequency have therefore to be very small near resonance in order to isolate an NNM motion. Furthermore, in the case of strong nonlinearities where a jump occurs in the frequency response function (FRF) in the vicinity of the resonance even small perturbations lead to a premature jump and require the experimentalist to start the elaborate tuning process all over again. Due to this extensive effort for the appropriation of a single NNM typically the invariance property of the invariant manifold of the associated free and damped system is exploited to extract the remaining NNMs of the same branch: Once the NNM is isolated by an appropriate force, the excitation is switched off and it is assumed that the motion of the damped system decays on the invariant manifold of the free and damped system. For light damping the motion of the free and damped system closely resembles the motion of the free and undamped system, i.e. the NNM motion. Due to the dissipation the vibration energy decreases successively such that an approximate NNM motion for different energy levels can be obtained. To extract the frequency-energy dependence of the NNM, a time frequency analysis is carried out on the recorded free-decay data. This requires sophisticated signal processing such as wavelet transform (WT) [15], Hilbert transform [16] or short time Fourier transform [17] and the degree of damping limits the resolution of the recorded backbone curve. The influence of transient effects is not clear for all systems, particularly when the excitation system, e.g. the shaker, remains connected to the structure during free-decay measurement. Moreover, there exists no method for the evaluation of the quality of the NNMs obtained by analyzing the free-decay data.

This paper presents a new approach for phase resonance testing to overcome the practical issues of the previous method. Therefore, the objective of the paper is twofold: Firstly, criteria for the evaluation of the NNM quality are derived and secondly a user-friendly way of force appropriation is presented. For the evaluation of the NNM quality a series of steady-state measurements for varying excitation levels is used instead of the free-decay measurements that are used in traditional phase resonance testing. The time consuming tuning of the excitation frequency has therefore to be simplified in order to obtain results within reasonable time. Thereto, a Phase-Locked-Loop (PLL) controller is implemented. The PLL is used for maintaining the phase lag quadrature criterion for the fundamental harmonic of the excitation. The desired phase of the excitation is reached automatically and very fast by the closed loop control. The frequency of excitation is inherently obtained by the structure's response. Thus, additional benefits of phase control like its robustness in lightly damped systems and the possibility of stabilization of unstable branches can be exploited. By the use of steady-state measurements transient effects are eliminated and the resolution of the measured backbone curve can be chosen arbitrarily. Furthermore, the steady-state tests with a known excitation force make it possible to evaluate the quality of the NNM appropriation for every point on the backbone curve.

When an approximate fundamental harmonic forcing is used for the excitation of the structure it is not sufficient to solely consider the phase of the fundamental harmonic as a quality indicator for the NNM isolation, as higher harmonics may be present in the forced response as well as in the NNM motion. Therefore, Peeters proposed a response based modal purity index (MPI) [10], which basically considers the phase of the fundamental and higher harmonics of the response. This MPI is restricted to monophase motions and theoretically has to be evaluated for all points on the structure simultaneously, which requires high experimental effort. Moreover, the result is highly dependent on the number of harmonics considered [18]. In contrast, in this paper a novel, excitation power based mode indicator function (PBMIF) will be presented which is simpler to implement experimentally, more reliable and general. The central quantity which has to be considered to calcu-