System Identification of Jointed Structures: Nonlinear Modal Testing vs. State-Space Model Identification

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ABSTRACT

Two approaches for experimental identification of the nonlinear dynamical characteristics of jointed structures are investigated, (a) Nonlinear Modal Testing, (b) State-Space Model Identification. Both require only minimal a priori knowledge of the specimen. For method (a), the definition of nonlinear modes as periodic motions is used, in its generalized formulation recently proposed for nonconservative systems. The theoretically required negative damping compensating the frictional dissipation is experimentally realized by properly controlled excitation. This permits the extraction of modal frequencies, damping ratios and vibrational deflection shapes as a function of the vibration level. For method (b), a state-space model with multivariate polynomial nonlinear terms is identified from the vibration response to a properly designed excitation signal. Both methods are applied to a structure with bolted joints. The quality of the extracted modal and state-space models, respectively, is assessed by comparing model-based predictions of the forced vibration response to reference measurements.

Keywords: nonlinear system identification, nonlinear modes, force appropriation, Brake-Reuss beam, jointed structures

1 Introduction

Assembled structures often feature nonlinear contact interactions [1] which can significantly influence the dynamical behavior and lead to a dependence of vibration features on the vibration level. It is the present state of knowledge that vibrations of jointed structures cannot be modeled from first principles. Instead, empirical models have to be used, which rely heavily on experimental parameter identification and validation. An important experimental task is the extraction of dynamic models from measurements, i. e., system identification. In the past, numerous methods for nonlinear system identification have been developed [2], however, most of them are not applicable to systems with nonlinear damping as in the case of hysteretic dry friction in joints.

In this contribution, two promising approaches for nonlinear system identification of jointed structures are considered. The first is a nonlinear modal testing approach referred to as enforced phase resonance (EPR) testing. It is based on the extended periodic motion concept [3], a nonlinear mode definition explicitly applicable to nonlinearly damped systems. The second approach is an input-output identification technique, namely the polynomial nonlinear state-space (PNLSS) method, which has been recently applied to a numerical model of a single degree of freedom oscillator with a hysteretic nonlinearity [4].

2 Theoretical Background of the Identification Methods

2.1 EPR Testing

A nonlinear mode is commonly defined as a family of periodic motions of an autonomous system. Motions of damped autonomous systems decay with time. An extended periodic motion concept for nonlinear modes was therefore proposed in [3], where the periodic motions are enforced by suitably appropriated negative damping. It has been shown that this definition of nonlinear modes leads to an accurate representation of the forced response near resonances, for a wide range of test cases including jointed structures.
In the present work, a practical realization of the extended periodic motion concept is used [5]. Consider the following vibration system,

$$\mathbf{M}\ddot{\boldsymbol{q}} + \mathbf{K}\boldsymbol{q} + \boldsymbol{g}(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{f}^{\mathrm{ex}}. \tag{1}$$

Here, the system is described by generalized coordinates $\boldsymbol{q}$, the symmetric mass and stiffness matrices $\mathbf{M}$ and $\mathbf{K}$, respectively, and a vector $\boldsymbol{g}$ which may contain linear and nonlinear restoring and damping forces. The idea of EPR testing is to replace the aforementioned negative damping, proposed in the extended periodic motion concept, by a periodic external forcing $\boldsymbol{f}^{\mathrm{ex}}$ in phase resonance with the vibration response. The 90° phase lag between forcing and displacement response is enforced using a phase-locked loop controller. Then, the response is measured as the forcing amplitude increases, effectively tracking the system's backbone curve directly. From the measurements, amplitude dependent modal frequencies can be directly extracted. Based on a linear modal analysis, deflection shapes are mass-normalized and a modal amplitude is computed. Using power considerations, the modal damping ratio can be obtained.

2.2 PNLSS Identification

The purpose of the PNLSS identification [4] is to estimate a nonlinear state-space model in the form

$$\begin{cases} \boldsymbol{x}(t+1) = \mathbf{A}\boldsymbol{x}(t) + \mathbf{B}\boldsymbol{u}(t) + \mathbf{E}\mathbf{e}(\boldsymbol{x}, \boldsymbol{u}) \\ \quad\;\; \boldsymbol{y}(t) = \mathbf{C}\boldsymbol{x}(t) + \mathbf{D}\boldsymbol{u}(t) + \mathbf{F}\mathbf{f}(\boldsymbol{x}, \boldsymbol{u}) \end{cases} \tag{2}$$

Herein, $\boldsymbol{y}$ are the output states, in our case accelerations, $\boldsymbol{u}$ are input states, in our case excitation forces, and $\boldsymbol{x}$ are internal states. Nonlinearities are assumed in the form of multivariate polynomial $\mathbf{e}(\boldsymbol{x}, \boldsymbol{u})$ and $\mathbf{f}(\boldsymbol{x}, \boldsymbol{u})$. The unknown coefficient matrices $(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}), \mathbf{E}$ and $\mathbf{F}$ are determined by an optimization algorithm with the objective to minimize the deviation between the measured and simulated response. A broadband, multisine excitation with random phase is generated as excitation signal. It is applied in a periodic sequence of blocks to avoid transients.

3 Experimental Study

The comparison of the two approaches is performed by means of the Brake-Reuss beam [6], a benchmark structure for the investigation of jointed structures, featuring an interface with three bolts. The beam is hung from two strands of fishing line for the experiments and excited around the first mode with a shaker, coupled by a stinger. The models are identified independently based on different measurements. For EPR testing, the system is excited using the phase-locked loop controller implemented on a dSPACE MicroLabBox with increasing forcing level. The random phase multisine excitation signal used for PNLSS identification covers a frequency bandwidth from 75 to 225 Hz, and the amplitude is varied during the experiments. The LMS SCADAS Mobile system is utilized as a signal generator, and the force is measured by an impedance head while the response is recorded using four accelerometers distributed over the beam.

From the identified models, the frequency responses are synthesized using a constant forcing amplitude. Additionally, forced responses around the first mode are measured for validation purposes at the same excitation levels. The results can be seen in Fig. 1 for one exemplary setup. At low and high excitation level, the forced response is synthesized with moderate accuracy. Yet, at medium forcing level, both methods underestimate the amplitude significantly. Furthermore, both models predict slightly lower resonance frequencies, where the PNLSS model shows larger deviations to the comparison measurements especially for the lowest excitation level.

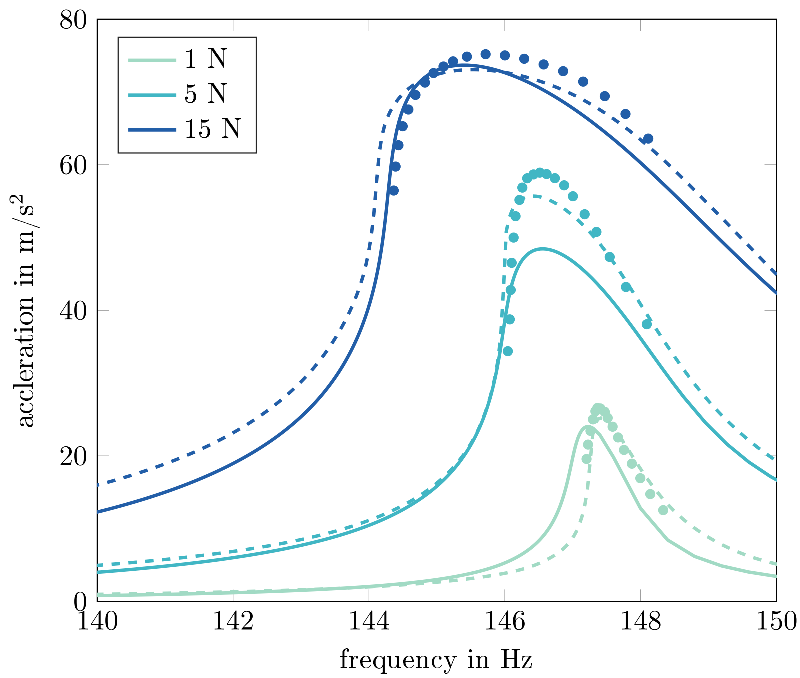

Fig. 1 Measured (*dots*) and synthesized frequency responses (*EPR dashed line*, *PNLSS solid line*) for three different forcing levels.

This work will be presented in more detail at the conference, in which the choice of input signals as well as the achieved model quality are discussed. Moreover, the variability of the measurements, caused by changes in the interface, is addressed. Finally, the methods are compared more thoroughly regarding the prediction capabilities for different forcing scenarios, including steady-state vibrations and fast sine sweeps.

4 Conclusion

Both EPR testing and PLNSS identification can be used to extract dynamic models of jointed structures. The model quality is deemed satisfactory in the considered range near the first resonance, giving the high measurement variability encountered for the considered benchmark system. Further work, involving more reproducible benchmarks, is required to explore and better understand the limitations of the methods for experimental characterization of jointed structures.

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