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Model reduction and frequency residuals for a robust estimation of nonlinearities in subspace identification

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ABSTRACT

The introduction of the frequency-domain nonlinear subspace identification (FNSI) method in 2013 constitutes one in a series of recent attempts toward developing a realistic, first-generation framework applicable to complex structures. If this method showed promising capabilities when applied to academic structures, it is still confronted with a number of limitations which needs to be addressed. In particular, the removal of nonphysical poles in the identified nonlinear models is a distinct challenge. In the present paper, it is proposed as a first contribution to operate directly on the identified state-space matrices to carry out spurious pole removal. A modal-space decomposition of the state and output matrices is examined to discriminate genuine from numerical poles, prior to estimating the extended input and feedthrough matrices. The final state-space model thus contains physical information only and naturally leads to nonlinear coefficients free of spurious variations. Besides spurious variations due to nonphysical poles, vibration modes lying outside the frequency band of interest may also produce drifts of the nonlinear coefficients. The second contribution of the paper is to include residual terms, accounting for the existence of these modes. The proposed improved FNSI methodology is validated numerically and experimentally using a full-scale structure, the Morane-Saulnier Paris aircraft.

1. Introduction

The need to embrace nonlinear behaviour mounts further in industry as increasing technological, economic and environmental pressures are faced. A large body of literature exists regarding the identification and dynamic testing of nonlinear structures, but very little work addresses real-life applications [1]. Most existing methods rely on linearisation or on the definition of equivalent linear modal parameters that vary with the forcing amplitude, as, e.g., described in Ref. [2]. Methods formulated in modal space were also proposed at DLR [3] and by Wright and co-workers [4]. All these approaches have their own merits, specifically they may be compatible with standard test practices. However, they generally assume that the structure under test vibrates in a weakly nonlinear regime of motion, which is a restrictive hypothesis. To offer an example, Weiland and Link proposed a method for the identification of weak nonlinear systems [5,6], based on a linearized set of system's equations, basically derived from the classic Harmonic Balance approach, with assuming that nonlinear terms depend

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individually on each degree-of-freedom response amplitude and that existing coupling effects are negligible. For these reasons, nonlinear system identification has not reached yet the same level of maturity as linear system identification, which is routinely applied to engineering structures [7], in particular to aircraft structures [8].

The introduction of the frequency-domain nonlinear subspace identification (FNSI) method in 2013 [9] constitutes one in a series of recent attempts toward developing a realistic, first-generation framework applicable to complex structures. The FNSI method is a nonlinear generalisation of the well known subspace identification algorithms [10,11], which are widely used for linear system identification [12,13]. The FNSI method derives models of mechanical systems possessing localised nonlinearities directly from measured data and without resorting to a preexisting numerical model, e.g. a finite element model [11]. The method pursues the twofold objective of identifying the underlying linear system, on one side, and, on the other, the lumped nonlinearities. FNSI is applicable to multiple-input, multiple-output structures with high non-proportional damping and high modal density, and makes no assumption as to the importance of nonlinearity in the measured dynamics [9]. The key to the method is the interpretation of nonlinear forces as feedback forces applied to the underlying linear structure, which allows high-dimensional inverse problems and strongly nonlinear regimes of motion to be tackled. The effects of lumped nonlinear inputs in the system are represented by using a linear-in-the-parameters model of the essentially nonlinear, i.e. nonlinearizable, restoring force vector encompassing elastic and dissipative contributions, which is, thus, expressed by a linear combination of suitable nonlinear basis functions with associated nonlinear coefficients. FNSI was validated numerically using simple [9] and more realistic systems [14], and experimentally using an academic setup [15].

There is still a number of limitations in the FNSI method which needs to be addressed. In particular, the removal of nonphysical poles in the identified nonlinear models is a distinct challenge. Similarly to linear system identification, the order of the model is selected in the FNSI approach using a so-called stabilisation diagram. As the model order is increased, the diagram features nonphysical poles, mainly resulting from linear modelling errors, i.e. an overestimation of the model order, nonlinear modelling errors, and noise perturbations. These poles have been shown to strongly perturb the estimation of the nonlinear coefficients [16]. A recent and effective procedure to deal with spurious poles in nonlinear subspace identification is due to Marchesiello and co-workers [17]. They interpret nonlinear coefficients as the ratio of two so-called extended frequency response functions, and perform truncated modal expansions of its numerator and denominator. This allows nonphysical modes to be eliminated during the computation of the nonlinear coefficients. The drawback of this procedure is that spurious poles are not eliminated from the original state-space model and, hence, contaminate model-based output simulations.

In the present paper, to carry out spurious pole removal, we propose, as a first contribution, to operate directly on the identified state-space matrices. A modal-space decomposition of the state and output matrices is examined to discriminate genuine from numerical poles, prior to estimating the extended input and feedthrough matrices. The final state-space model thus contains physical information only and naturally leads to nonlinear coefficients free of spurious variations. Besides spurious variations due to nonphysical poles, vibration modes lying outside the frequency band of interest may also produce drifts of the nonlinear coefficients. The second contribution of the paper is, therefore, to include residual terms accounting for the existence of these modes.

The paper is organised as follows. In Section 2, the removal of spurious poles in modal space and the introduction of lower and upper frequency residuals are discussed in detail. In Section 3, the proposed methodology is numerically validated through the usage of a full-scale structure, the Morane-Saulnier Paris aircraft (see Fig. 1). This aircraft features nonlinear bolted connections, modelled herein as cubic stiffness characteristics. Experimental data acquired on the aircraft structure are finally exploited in Section 4 to demonstrate the methodology in the presence of nonlinear modelling errors and noise. The conclusions of the study are summarised in Section 5.

Fig. 1. The Morane-Saulnier Paris aircraft at ONERA's Laboratory.