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A new, challenging benchmark for nonlinear system identification

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ABSTRACT

The progress accomplished during the past decade in nonlinear system identification in structural dynamics is considerable. The objective of the present paper is to consolidate this progress by challenging the community through a new benchmark structure exhibiting complex nonlinear dynamics. The proposed structure consists of two offset cantilevered beams connected by a highly flexible element. For increasing forcing amplitudes, the system sequentially features linear behaviour, localised nonlinearity associated with the buckling of the connecting element, and distributed nonlinearity resulting from large elastic deformations across the structure. A finite element-based code with time integration capabilities is made available at https://sem.org/nonlinear-systems-imac-focus-group/. This code permits the numerical simulation of the benchmark dynamics in response to arbitrary excitation signals.

1. Introduction

The use of benchmark systems plays an important role in research fields experiencing very rapid growth. They provide standard problems by which the performance of various solution approaches can be evaluated. The definition of performance may vary depending on the field of interest, but usually refers in engineering to notions of accuracy, versatility, time and computational efficiency, and easiness of implementation and utilisation. In the structural dynamics community, benchmarking is not a new idea [1,2]. During the nineties, benchmark systems contributed to the maturity of experimental modal analysis [3,4]. More recently, benchmark data were made available to foster progress in disciplines like structural health monitoring and diagnostics [5–9], contact and joints modelling [10,11], operational modal analysis [12], and substructuring [13].

The considerable progress accomplished during the past decade in nonlinear system identification in structural dynamics [14] was also partly driven by the existence of benchmark systems. The most noticeable example is the *Ecole Centrale de Lyon* (ECL) benchmark introduced in 2003 in the framework of the European COST Action F3 [15,16]. It is an experimental system comprising a thin beam behaving as a cubic stiffness component connected to a linear thick beam with well-separated, lowly-damped modes. It has been intensively exploited in the technical literature to demonstrate newly-introduced methods in nonlinear structural dynamics, while slight variants of the original setup were also proposed, e.g., in Refs. [17,18]. The fair complexity of this benchmark is arguably the reason for its great success.

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The objective of the present paper is to consolidate the recent advances in the field by challenging the community through a new benchmark structure exhibiting complex nonlinear dynamics. The proposed structure consists of two offset cantilevered beams connected by a highly flexible element. For increasing forcing amplitudes, the system sequentially features linear behaviour, localised nonlinearity associated with the buckling of the connecting element, and distributed nonlinearity resulting from large elastic deformations across the structure. This system identification benchmark was initially devised in the context of a round-robin session organised at the 32nd International Modal Analysis Conference (IMAC), held in Orlando, Florida, USA, 3–6 February 2014, where it received significant attention.

The focus of the benchmark problem described in this paper is put on the identification of geometric nonlinearities, motivated by their increasing importance in various engineering applications. Geometric nonlinearities may be the result of large deformations in highly flexible slender structures, such as aircraft wings [19], wind turbine blades [20], cable-stayed bridges [21], or off-shore structures [22]. They may also be responsible for hardening-softening resonances, as observed in academic and micromechanical cantilever systems in Refs. [23,24], respectively. Buckled beams and panels, which find application in high-speed aircraft designs, are other typical examples of structural components exhibiting nonlinear behaviour due to geometric arguments [25]. Finally, it is worth noting the potential of geometric nonlinearities for vibration absorption [26] and energy harvesting [27].

It is believed that the benchmark problem introduced herein may stimulate research interest in a number of open questions in the system identification field, namely:

- can location techniques discriminate between localised and distributed nonlinearity manifestations according to forcing amplitude?
- can nonparametric approaches provide, with minimum user interaction, insight towards selecting an appropriate mathematical description of the nonlinearities?
- can classical polynomial basis functions be used for modelling geometric nonlinearities involving buckling, i.e. complex elastic restoring forces with abrupt slope changes?
- can nonlinear modal identification methods outperform physical-space methods in the identification of distributed nonlinearity? A first attempt to answering this question using benchmark data is reported in Ref. [28].
- can black-box models of the structural behaviour with a reasonable number of parameters be derived?
- can bifurcations be detected and characterised in the benchmark dynamics?

The paper is organised as follows. A detailed physical description of the benchmark is given in Section 2. As the reader may find difficult to translate this description into exploitable data, being either numerical or experimental, a finite element-based code with time integration capabilities is made available at https://sem.org/nonlinear-systems-imac-focus-group/[1]. This code, presented in Section 2, permits the numerical simulation of the benchmark dynamics in response to arbitrary excitation signals. In Section 3, static stiffness curves and transient responses generated using the offered finite element package are analysed, highlighting the richness and complexity of the benchmark nonlinear dynamics. In particular, the wavelet transform of a decaying displacement time history reveals a dramatic softening of certain resonance frequencies of the structure. Conclusions are finally summarised in Section 4.

2. Physical description and numerical implementation

The considered structure consists of two clamped beams joined using a highly flexible element, as illustrated in Fig. 1. The left and right beams, denoted 1 and 2 in Fig. 1, respectively, lie 20 mm apart on parallel planes, so that the connecting element is inclined. Their length is 300 mm, their width is 20 mm and their thickness is 6 and 5.5 mm, respectively. The linear elastic material adopted for the two beams is characterised by a Young's modulus $E_b = 210$ GPa, a Poisson ratio $\nu_b = 0.33$, and a density $\rho_b = 7800$ kg/m^3. The connecting element is about 63-mm long (the exact length is $\sqrt{60^2 + 20^2}$), 20-mm wide and 0.5-mm thick. It possesses a Young's modulus $E_c = 42$ GPa, a Poisson ratio $\nu_c = 0.33$, and a density $\rho_c = 540$ kg/m^3. Linear viscous damping is added to all translational degrees of freedom (DOFs), given a proportionality coefficient between damping force and velocity equal to 3.16 10^{-2} Ns/m. Table 1 lists the linear natural frequencies and damping ratios of the structure in the 0–1000 Hz frequency range. The corresponding modal shapes are depicted in Fig. 2.

A numerical model of the structure was developed using the shell elements discussed in Ref. [29]. The adopted shell element is triangular and possesses 3 nodes with 6 DOFs (3 translations and 3 rotations) per node. It is based on the element developed by Allman [30], and enriched with linear shape functions for the out-of-plane DOFs to represent quadratic strain components. The element size is 10 mm. It was evaluated that refining the mesh size by a factor 2 leads to relative differences in the first 10 linear natural frequencies of maximum 0.35%, proving acceptable mesh convergence. The selected finite element mesh, displayed in Fig. 3, comprises 816 DOFs. It guarantees reasonable simulation efforts when long time histories are required, considering that the cost of the Jacobian assembly and factorisation scales with the square of the

[1] Alternatively, the interested reader should contact the authors directly.

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