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Modal interactions due to friction in the nonlinear vibration response of the "Harmony" test structure: Experiments and simulations

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ABSTRACT

The nonlinear vibration response of an assembly with friction joints – named "Harmony" – is studied both experimentally and numerically. The experimental results exhibit a softening effect and an increase of dissipation with excitation level. Modal interactions due to friction are also evidenced.

The numerical methodology proposed groups together well-known structural dynamic methods, including finite elements, substructuring, Harmonic Balance and continuation methods. On the one hand, the application of this methodology proves its capacity to treat a complex system where several friction movements occur at the same time. On the other hand, the main contribution of this paper is the experimental and numerical study of evidence of modal interactions due to friction. The simulation methodology succeeds in reproducing complex form of dynamic behavior such as these modal interactions.

1. Introduction

The "Harmony" test structure has been designed to study the effects of friction on the frequency response of an assembly. In a previous work [1], an experimental and numerical study was undertaken on this structure. The experimental frequency response of the assembly to an axial excitation has been studied, highlighting the damping and softening effects due to friction. A methodology which groups together well-known methods of structural dynamics has been proposed to model the structure and simulate its vibration response. Firstly, each component of the assembly and the assembly itself are modeled using finite elements. These models are updated to fit experimental vibration responses at a low excitation level. The assembly model is then reduced using a substructuring algorithm [2]. The nonlinear behavior of the friction joints is introduced at this step: the linear connectors which model joints are replaced by nonlinear elastic Coulomb models. The nonlinear dynamic system obtained is solved using the Harmonic Balance Method [3] coupled with a condensation process [4] and a continuation method. The simulation results obtained reproduce the damping and softening effects due to friction.

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This initial work has thus proved the capacity of the proposed methodology to simulate the effects of friction in a complex assembly.

In the present paper, the response of the "Harmony" test structure to a transverse excitation is studied. The simulation methodology, based on the Harmonic Balance Method with condensation and predictor–corrector processes, is applied. The first contribution of this new study is to prove the capacity of the methodology to treat a case where diverse friction movements occur at the same time (both translations and rotations occur in the friction movement of the joints). Subsequently, the main contribution of this paper is the experimental and numerical study of modal interactions due to friction. A key element of this study is the use of a 3D scanning laser vibrometer to measure the local strain of the friction joints. For many decades, it has been well known that nonlinear terms in dynamic equations can induce strong energy exchanges between modes (see [5,6] and references therein). These exchanges can be also referred to modal interactions or internal resonances. When the energy of a main mode is partially transferred to its nth harmonic, it is generally denoted as a 1:n modal interaction. Modal interactions were first studied on systems with very few degrees of freedom. In [7] a 1:2 internal resonance is studied both theoretically and numerically on a two degrees of freedom system. The 1:2 modal interaction made it possible in particular to explain the undesirable roll characteristics of ships that sailors have known for centuries [8]. Many studies of modal interactions in geometrically nonlinear structures such as beams and plates can be found in [6]. Multiple mode interactions have also been studied for tuned structures such as musical instruments [9–11]. Very few studies focused on modal interactions in industrial assemblies. Recently, Noël, Renson and Kerschen [12,13] highlighted modal interactions both experimentally and numerically in the vibration response of an industrial space structure where the nonlinear behavior comes from piecewise linear joints. The main contribution of the present paper is therefore to present modal interactions due to friction in an industrial assembly. These interactions that are most often unexpected in industrial studies can lead to major design issues and thus need to be studied using nonlinear dynamic methods.

Section 2 presents the experimental results obtained exciting the "Harmony" test structure in a transversal direction. The experimental responses have been measured using both accelerometers and a 3D scanning laser vibrometer. Modal interactions are evidenced. Section 3 details the modeling methodology. Finally, Section 4 presents the simulation method and compares the simulated results with the experiments.

2. Experiments

Experiments were performed with a shaker, accelerometers and an experimental protocol that correspond to industrial standards. In addition, a 3D scanning laser vibrometer was used to study the local slipping movement in the joints. This section presents the experimental set-up, the results obtained and focuses on modal interaction evidences.

2.1. Experimental set-up

The "Harmony" test structure is presented in detail in [1]. It is an assembly of two main parts: a central body and an external envelope the dimensions of which are presented in Table 1. The bottom of the central body is clamped to the envelope and its top is in contact with this envelope through four blades. At high excitation level, it was demonstrated that friction appears in these contact joints [1]. In the present work, the structure is excited horizontally. The experimental set-up is presented in Fig. 1. The assembly is clamped to a moving table that is excited by an industrial shaker. The shaker is piloted in order to control the acceleration of the moving table so that the excitation level is the horizontal acceleration (along the x-axis) of the moving table. This acceleration is measured using the accelerometer situated on the base plate (see point A10 in Fig. 1).

2.2. Experimental results

Firstly, swept sine experiments are realized at a low excitation level ($1\ \mathrm{m\,s^{-2}}$) over a large frequency range 5–2000 Hz. These data are used to update and validate the finite element model. The experimental modes are identified at 134.7 Hz, 309.0 Hz, 1240 Hz, 1675 Hz and 1826 Hz. The experiments then focus on the first horizontal mode. Swept sine experiments are performed in the vicinity of this mode with increasing excitation levels. The results obtained at the top of the central

Table 1
Parts characteristics.

Part	Material	Dimensions (mm) Max radius, height	Mass (kg)
Central body	Stainless steel 304L	160, 300	11.92
External envelope	Stainless steel 304L	204, 420	44.88
Base plate	Aluminium 2017A	218, 25	8.67
Blade (x4)	High resistance steel Z8-cnd17-04	65, 118	0.1086

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