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Experiments and numerical simulations of nonlinear vibration responses of an assembly with friction joints – Application on a test structure named "Harmony"

M. Claeys [a,b,1], J-J. Sinou [b,c,*], J-P. Lambelin [a], R. Todeschini [a]

[a] CEA/CESTA, CS60001, 15 av. des Sablières, 33116 Le Barp, France
[b] Laboratoire de Tribologie et Dynamique des Systèmes UMR-CNRS 5513, Ecole Centrale de Lyon, 36 avenue Guy de Collongue, 69134 Ecully Cedex, France
[c] Institut Universitaire de France, 75005 Paris, France

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ABSTRACT

In presence of friction, the frequency response function of a metallic assembly is strongly dependent on the excitation level. The local stick-slip behavior at the friction interfaces induces energy dissipation and local stiffness softening. These phenomena are studied both experimentally and numerically on a test structure named "Harmony".

Concerning the numerical part, a classical complete methodology from the finite element and friction modeling to the prediction of the nonlinear vibrational response is implemented. The well-known Harmonic Balance Method with a specific condensation process on the nonlinear frictional elements is achieved.

Also, vibration experiments are performed to validate not only the finite element model of the test structure named "Harmony" at low excitation levels but also to investigate the nonlinear behavior of the system on several excitation levels. A scanning laser vibrometer is used to measure the nonlinear behavior and the local stick-slip movement near the contacts.

1. Introduction

In the past, the vibration responses of industrial structures were mainly studied using a linear analysis. Indeed, numerical simulations for both modal analysis and Frequency Response Function of linear systems are implemented in every Finite Element software and are widely used in industry. However, experimentally, the frequency response of an assembly often appears to be strongly dependent on the excitation level which cannot be explained by a classical linear analysis. This nonlinear evolution may be due in particular to friction in the joints, large displacements, non-elastic materials or contacts [1,2].

Therefore, the incorporation of nonlinear phenomena into complex mechanical systems currently gives rise to major problems during the design of industrial mechanical structures. It is clear that optimizing mechanical structures with respect to their vibration behavior requires a detailed understanding of the structures along with a highly refined model. Including the set of nonlinear elements that play a predominant role in the dynamic behavior of structures, proves essential

* Corresponding author.
E-mail address: jean-jacques.sinou@ec-lyon.fr (J.-J. Sinou).
[1] Tel.: +33 0 472186466; fax: +33 0 472189144.

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not only to studying the dynamic behavior of systems, but also to devising robust and reliable system designs able to withstand the range of loadings potentially applied. So both an efficient modeling of the nonlinear behavior of mechanical systems and the development of nonlinear computational techniques are essential in order to proceed with an efficient and quick analysis of complex problems. It is known that various computational techniques in the treatment of nonlinear differential equations have been proposed in a wide range of mechanical engineering problems [3–5]. According to Sarrouy and Sinou [6] the Harmonic Balance Method is one of the most popular methods for approximating the stationary nonlinear responses of mechanical systems. The main idea of this numerical process is to approximate the nonlinear responses and the nonlinear forces in dynamical systems by their Fourier series. This method was implemented in a previous work of the authors [7] and compared with the method of multiple scales and the shooting method for the computation of the nonlinear response of nonlinear systems. It was illustrated that the Harmonic Balance Method gave excellent results in terms of both precision and computation time. This is the reason why this method has been chosen for the present study. In the recent years, many efforts have also been done to increase the numerical efficiency of this nonlinear approach for vibration damping by dry friction [8–13]. Among them, we can cite the Dynamic Lagrangian Frequency Time method (DLFT), proposed by Nacivet et al. [14] that enables to handle directly the non-smooth unilateral and frictional contact laws.

Also, conducting studies with experiments, modeling and numerical simulation seems necessary nowadays in order to better understand the limitation of modeling and to increase the confidence of the numerical models with nonlinear frictional elements. One of the primary objectives is also that the numerical model can be used to minimize the need for conducting expensive experiments for optimizing such mechanical structures. Some previous works have already presented this type of study that combines experimentation and simulation in the field of structures with friction joints. This is more specifically the case in the field of turbomachinery bladed disks for which significant vibration damping by friction forces can occur. Therefore the friction damping concept has been frequently applied in turbomachinery applications and various research works for analyzing the dynamic characteristics of structures with friction joints have been undertaken. For example we can mention researches on structures with underplatform dampers [15–19], approach for characterizing the dynamic behavior of a friction damper [20], shrouds with a frictional interface to reduce the dynamic stresses in turbine blades via the comparison between measured and calculated frequency response functions for bending and torsional vibrations of the blade [21], optimization of interblade friction damper design with respect to an optimal damper geometry and damper mass [22], impact of friction in blade with root joints [23] or friction rings [24]. More generally, the review papers of Gaul and Nitsche [25] and Feeny et al. [26] provided also a historical overview of structural and mechanical systems on the general topic of friction damping.

In the present study, we propose to investigate the nonlinear behavior of a complex structure, “Harmony”, which includes nonlinear frictional elements. Results from the nonlinear numerical simulations are compared with those from various experiments. Even if the primary objective of the present study is the validation of existing numerical methods, one of the main contributions is to be able to perform measurements of nonlinear vibrations near the contacts by using a scanning laser vibrometer, providing the opportunity to compare experiments with the numerical results.

The paper is divided into three parts. Firstly, a brief description of the test structure and the analysis of various experimental data from vibrational tests on a bench in the CEA laboratory are presented. Secondly, the paper focuses on the finite element modeling (linear elements, model reduction and frictional modeling) and the global updating procedure. The nonlinear simulation based on the well-known Harmonic Balance Method with a condensation process is then explained in Section 4. Finally, results from the nonlinear numerical simulations are compared with those from experiments. Multi-harmonic comparisons are performed [7] and a local analysis of the stick-slip movement is also proposed. This last part is one of the originality and peculiarities of the study that proposes to increase the confidence in the numerical models currently used for friction damping simulation by providing comparisons between experiments and simulations in the neighborhood of the contact interface.

2. Experiments

2.1. Motivations

In presence of friction, the Frequency Response Function (FRF) of an assembly evolves while increasing the excitation level. The resonance peaks may flatten or sharpen with the increase of the excitation level when the resonance frequencies are lowered. The objective of the experimental part of this study is to reproduce experimentally these phenomena on a structure where the origins of friction are obvious. This objective led to the design of a specific test structure named “Harmony”. This proposed test structure includes four contact joints (identified a priori) where friction is expected at high excitation levels. “Harmony” is designed with a minimal number of joints so as to be able to limit the sources of nonlinear behaviors and energy dissipation. Therefore, it enables to fully understand the concept of modeling nonlinear friction connections and their impacts through experimental tests and comparisons with numerical simulation. Yet the structure is complex enough to demonstrate the ability of the proposed simulation method to be applied on real industrial structures with nonlinear friction connections. The experiments are performed in an industrial way, with an industrial shaker and accelerometers to measure experimental FRF. In addition, specific instrumentation is used to record the local stick-slip movement related to friction in a joint zone. A scanning laser vibrometer is thus additionally deployed. The two main