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Study of the dynamic behavior of a bolted joint under heavy loadings

Sami Daouk [a], François Louf [a,*], Christophe Cluzel [a,b], Olivier Dorival [c,d], Laurent Champaney [a], Sylvie Audebert [e]

[a] LMT, ENS-Cachan, CNRS, Université Paris Saclay, 94235 Cachan, France
[b] IUT-d'Evry Val d'Essonne, Dep. SGM, 91025 Evry, France
[c] ICAM–Site de Toulouse, 31076 Toulouse, France
[d] Université de Toulouse, Institut Clément Ader UMR CNRS 5312, INSA/UPS/ISAE/Mines Albi, France
[e] EDF R&D, EDF Lab PARIS-SACLAY, 91120 Palaiseau, France

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ABSTRACT

In structural dynamics, the quantification of the quality and reliability of numerical models remains a relevant issue. While the behavior of structures such as beams and plates is generally understood, a large number of industrial structures are bolted assemblies of many components with connections that are not well understood. The main reason for this lack of understanding is that the dynamical behavior of the whole assembly depends critically upon joint conditions, especially under heavy loadings. For the purpose of improving our understanding and the development of pertinent models, a dynamic test bed, based on a bolted structure, is designed and modal testing is performed. The configuration of the bolted joint and the level of the loading are the relevant parameters, related to joint conditions, that are considered in this study. The results of the experimental campaign show the variation of the dissipation in a bolted joint and its apparent stiffness as a function of joint conditions.

Introduction

The dynamical behavior of industrial assemblies has to be reliably understood in order to avoid accidents that would endanger the safety of people and facilities. In particular, the dynamic behavior of mechanical systems in nuclear plants has to be predicted with full confidence. The stiffness of these assembled structures results from keeping relatively flexible components in position with many fasteners such as preloaded bolts. These fasteners contribute to the distributions of stiffnesses and masses in the assembly in a complicated way, making the system nonlinear and generating uncertainties and variabilities [22,15].

Many difficulties encountered when analyzing nonlinear systems come from a lack of understanding of the physical nonlinear phenomena. As a result, small modifications in modeling nonlinear elements can lead to substantial discrepancies between the responses of the system [6,7]. In fact, even though the sources of uncertainties can be identified, the characterization of their impact on the dynamic behavior of the system is still not clear. Therefore, when studying the dynamics

* Corresponding author.
E-mail address: francois.louf@lmt.ens-cachan.fr (F. Louf).

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of bolted joints, the lack of a deep complete comprehension of what happens in the contact zones raises prominent questions:

- How are the damping and stiffness of the system influenced by the presence of bolted joints ?
- How do the damping and stiffness of the system vary depending on the excitation level of the system ?

From a fundamental viewpoint, the effects linked to the contact of two surfaces on the dynamic behavior are the subject of many experimental research activities. For instance, the effects of normal loadings are studied in [2] and the effects of shear uniform slip are presented in [30]. Naturally, modeling these friction problems from the description of micro-slips and their impact on damping are also the subject of numerous analyses. In [32], different bolted joints of thin plates are studied and the evolution of dissipation as a function of the frequency, the amplitude and the mode are presented. In [21], we see that running-in fatigue effects of surfaces have an impact on damping functions. In [16,22], the bolt preload is the added parameter. We find in [18] a review of models and applications on different types of bolted joints. Two conclusions are that the choices of models depend on the application type and that the variations of friction properties and of contact forces distributions generate high dispersions of joint stiffness and damping. Simulations of nonlinear friction contact effects of two bolted plates under shearing are presented in [29] via a local finite elements contact analysis and a more global modeling of the joint. However, in this study too, a conclusion is that the variability of the structure responses forces to experimentally update the parameters on a joint of the same type as the one used.

In addition, many authors analyse joints directly via tests on mini-structures using a particular technology, then exploit the results to simulate the effects of small joint modifications or understand the influence of loadings on dissipation. Hence, we find in [9,24] an experimental identification of dissipations in bolted joints of space launcher structures (SYLDA). Then, in [10], a numerical exploitation is carried out after updating friction parameters, including their fatigue evolutions. In [28], all components of a bolted and glued joint between two satellite sandwich panels are studied experimentally. The authors of [20] introduce the effects of viscoelastic damping of elastomer layers in a structural aircraft joint.

Moreover, in relation to joint conditions, the study of a two-beam stainless steel structure coupled by three bolts [8] shows that the presence of a bolted joint has a significant impact on the frequency response functions of the system. In particular, the results of this study showed that the torsional modes are sensitive to the interfacial conditions and that the bending modes are sensitive to the bolt preloads and the order in which the bolts are tightened. In order to distinguish the effect of the mechanical joint from other sources of uncertainty and nonlinearity, a second study on the same structure was conducted [31]. Its focus is on the effects of different loading conditions, measurement techniques and boundary conditions on the response of the system. Another experimental study has been recently performed on a portal frame containing elementary steel-aluminum bolted joints [33]. The results show that input parameters such as the bolt preload and the tightening order have a notable impact on some natural frequencies but the loading level was low and not controlled.

The vast majority of these articles describes interfaces between two bolted planes subject to local shear stresses. When joints are thin and are subject to transverse moments or loadings, the levels of interfacial stresses are quickly significant and generate micro-slips. Very few articles study massive structures having a joint plan normal to the average direction of the structure. The structure used as a reference in this article is a large booster bump, with a massive body, large diameter joints and a rotating axis. A great part of the bolted assemblies used in rotating machinery are subject to high loading and vibration levels. The understanding of their dynamical behavior under such conditions turns out to be crucial during their design. However, most of the research studies conducted in this field consider joints comprising few bolts with low preloads and low excitation levels. In order to generate significant slips, the loading level of such joints has to be very high which creates experimental difficulties if precise measurements are requested. In addition, analyzing a symmetric mode means that slips cannot occur in the joint faces. The usual joint place slip models are then baseless and experimental data is necessary. This is the purpose of this article, leading thereafter to the estimation of uncertainties on prediction of damping and natural frequencies. Consequently, we show the design of a dynamic test bed containing a configurable bolted joint, then consider heavy loadings and examine the experimental variability due to the variation of joint conditions.

The first part of this paper describes the specifications, the basic ideas and the iterative sizing procedure of this test bed. The second part presents the experimental procedure and the first results of modal testing of the assembly. In the third part, global experimental results (variation of dissipation and natural frequencies) obtained on the first bending mode of the assembly are presented and discussed. The fourth part presents the exploitation of experimental results on the level of the joint of interest in order to describe the evolution of the dissipation in the joint and its apparent stiffness depending on joint conditions.

1. Design of the assembly

1.1. Context of the study and related technical specifications

The work presented in this paper is carried out in partnership with EDF R&D and thus should be representative of its industrial assemblies such as booster pumps used in thermal units. These assemblies comprise bolted joints having the following features: the bolted parts are metallic, massive, the joint is plane and has a large diameter containing many bolts