

Experimental and theoretical studies of a bolted joint excited by a torsional dynamic load

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Abstract

This paper presents the experimental work on a single joint rig and the analytical models for representing the experimental results. A bolted joint connecting two beams is shaken at two resonant frequencies. These experiments have illustrated microslip and macroslip phenomena from measurements taken locally to the joint interface in the time domain. Hysteresis loops of the torque versus the relative angular displacement of the joint have been generated from the time-domain data of the rig subjected to multiple bolt preloads and amplitudes of excitation. Damping behaviour evolving from linear viscous type to nonlinear frictional type is clearly shown in the plots of the hysteresis loops and the frequency spectra of the relative angular displacement of the joint. As microslip in the joint develops, the hysteresis loops deviate from an ellipse and the contribution from superharmonics in the frequency spectra becomes stronger. The presence of odd superharmonics in the frequency spectra seems to suggest that the nonlinearity due to friction in the joint can be represented by a cubic stiffness term. The Jenkins-element model for the friction torque in the joint has been used to fit the hysteresis loops of the experimental joint.

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1. Introduction

Many structures are built up by connecting structural members through joints. Due to very low material damping of built-up structures, sufficient damping has to come from the joints. In structures made up of bolted members, up to 90% of the damping can be supplied by the joints themselves [1]. Energy is dissipated through small amounts of sliding contact, known as microslip, taking place in local regions of the joint interface. Microslip is defined as a small relative tangential displacement in a contacting area at an interface, when the remainder of the interface in the contacting area is not relatively displaced tangentially [2]. In contrast, macroslip takes place when the whole contacting area experiences a relative displacement. Frictional energy dissipation is a highly nonlinear process and when coupled with the dynamic contact happening at a

joint interface proves a challenging phenomenon to characterise in an analytical expression.

A bolted joint displays a hysteresis loop for the force occurring in the joint versus the local (relative) displacement of the joint when subjected to harmonic longitudinal excitation, torsional excitation or bending excitation [3]. Reviews on joint friction were presented by Ferri [4], Gaul and Nitsche [5], and very recently by Ibrahim and Pettit [6]. In the study of bolted joints, experiments play a very important role. Gaul and his co-workers [3,5,7] excited their rigs at the resonant frequency to achieve sufficient slippage in the joint and established joint models with certain physical meanings. Ma et al. [8] used the swept sine to obtain the frequency response functions of two cantilever beams connected at the free ends by a bolted joint and of a companion beam (without a bolted joint) and by comparing the two functions established a non-parametric joint model. Ahmadian and Jalali [9] simulated the stiffness-softening behaviour of a similar structure.

Andrew et al. [10] showed that no significant energy loss occurred at preloaded flat metallic joints subjected to

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Nomenclature

k_0	spring constant of the permanent spring in the Jenkins-element model
k_i	spring constant of the i th spring in the Jenkins-element model
m	number of Jenkins elements in the Jenkins-element model
R_i	static friction capacity of the i th Coulomb element in the Jenkins-element model

p	bolt preload
sgn	the signum function
T	the amplitude of applied torque (Nm)
T_j	the frictional torque of the bolted joint
θ	the relative angular displacement of the bolted joint
θ_{rev}	the relative angular displacement of the bolted joint just before the velocity reversal
$\dot{\theta}_{\text{rev}}$	the relative angular velocity of the bolted joint just before the velocity reversal

normal excitation. This suggests that only the vibration in the tangential plane may be significantly damped by joints [11]. This vibration may be excited by a tangential load as in Refs. [11,12] or by a torsional moment as in Ref. [13].

This paper presents experimental results of a single bolted joint under torsional excitation at the resonant condition of the rig. By adding or removing a mass, the rig possesses two distinct first natural frequencies. This allows two different excitation frequencies to be used in the experiment. For each excitation frequency, various levels of bolt preload and/or amplitude of excitation are applied. Time-domain data are collected. From these data, hysteresis loops of the torque of the joint versus the (relative) angular displacement (rotation) of the joint can be plotted. Frequency spectra of the angular displacement are also produced. It is found that the frequency spectra have a single dominant peak for elliptic hysteresis loops and the superharmonic contribution in frequency spectra becomes stronger as the hysteresis loops deviate from elliptic shapes due to increasing frictional damping. In these situations, the Jenkins-element model, originally put forward to deal with hysteresis in the theory of plasticity, is used for representing the non-viscous, frictional damping behaviour. This model shows good correlation with the experimental hysteresis loops. It is also found that the hysteretic behaviour of the bolted joint at the two resonant frequencies is quite different when microslip is significant.

It is a challenge to design and make bolted joints that produce adequate damping yet maintain sufficient rigidity. A structure's dynamic response at resonance depends on damping. Its response to random excitation also depends on damping [14]. The knowledge of the damping behaviour of a bolted joint is useful in accurately predicting the dynamic response. It helps to understand and design semi-active and active joints, and to understand the dynamics of structures made with these joints. It may even be useful in understanding other types of joints as well.

Bolted joints present a dynamic frictional contact problem, which is very difficult to investigate and compute. Although friction and contact mechanics are important in joints, the authors are mainly interested in the dynamic response of bolted joints and built-up structures with bolted joints under excitation. As such, this is not treated as a friction-induced vibration problem. For that topic and

friction laws, the review papers by Oden and Martins [15] and Ibrahim [16] provide a comprehensive source of information.

2. Experimental procedure

2.1. Experimental set-up

In order to gain a good understanding of bolted joints, a rig was built and a series of experiments have been conducted. Analysis of the experimental data was then carried out and plausible analytical models were studied.

Tsutsumi and Ito [13] showed the relationship between the energy loss per cycle and the torsional moment of a bolted joint. Gaul and Bohlen [3] also studied the energy loss of a bolted joint under torsional excitation at its resonant frequency, made of two circular plates bolted together.

The joint tested for the experimental investigation was a lap joint shown in Fig. 1. The joint connects one cantilever beam and one 'free' beam and together they form the test rig shown in Fig. 2.

The jointed beams are configured at either side of the joint so that the joint interface lies in the same plane as the central plane of the two component beams. As a result, the excitation force applied at point B in Fig. 2a will produce a torque in the same plane of the joint interface, but not an unwanted torque that will twist the beams around their longitudinal axis. This arrangement is different from other experimental lap joints tested under bending excitation, for example, reported in Refs. [3,7,8], and under torsional excitation [3,13].

To generate a full range of microslip in the joint it was necessary to produce sufficient movement at the region where the frictional interface was located. On the free end

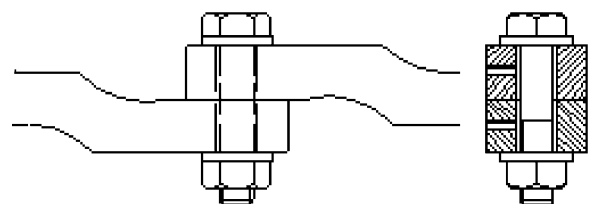


Fig. 1. The lap joint.

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