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Validation of a new frictional law for simulating friction-induced vibrations of rough surfaces

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ABSTRACT

Friction-induced vibrations are a complex phenomenon, arising when two surfaces undergo relative sliding. During the last decades many studies on friction-induced vibrations have been carried out, where the simulation of the contact dynamic excitation has always been a challenge to face. This work proposes a new method to reproduce the local dynamic excitation from the contact and its effect on the vibrational response of the system. A friction law including a perturbative term of the friction coefficient is introduced. The evolution of the perturbative term, recovered by dedicated experiments, allows for simulating and analysing the contact excitation mechanisms. The comparisons between numerical and experimental results show good correlation between the measured vibrations and the ones simulated numerically, validating the proposed friction law.

1. Introduction

Friction-Induced Vibrations (FIV) are a phenomenon which engages multiple scientific challenges due to the complexity of their physics; indeed several contact parameters can affect the response of the vibrating system, such as contact normal load [1–4], sliding velocity, surface roughness [2,5], component geometries, material properties, etc. Each change in one of the contact parameters influences directly the contact dynamics and the response of the system, due to the mutual influence of the local dynamics of the contact and the global system dynamics [6].

It has been highlighted [3] that, as a function of the contact load, the coupling between the contact and the system dynamics causes a variation between weak and strong contact conditions; the transition from uncoupled to coupled dynamics of the bodies in contact being the distinction between the two contact states. In fact, while for weak contacts the components respond with their own dynamics to the broadband excitation from the contact interface, the strong contact conditions imply the response of the coupled dynamics of the whole system [3,7,8].

While during weak contacts, the dynamic response of the system is generally stable, with strong contacts the coupling between system and contact dynamics can affect the dynamic stability of the system [9,10]. For instance, the transition to coupled conditions (strong contacts) can give rise to mode coupling instabilities [11], largely studied and involved in many mechanical issues, such us brake squeal and squeaking of hip endoprosthesis [12–18]. The need of a stochastic model for friction is attested by recent approaches from nonlinear dynamics, aimed to investigate the non-deterministic dynamics at interfaces by the nonlinear models [19–21]. The phenomenon of brake squeal, in particular, has been recently studied by the means of stochastic techniques, showing how the system response to the contact excitation, due to sliding friction, presents a chaotic structure and a multiscale character, changing behaviour from short to longer time scales [22,23].

In mechanics, another frequent instability phenomenon is the stick-slip motion. The nonlinear dynamic literature attributed generally such behaviour to the difference between static and kinetic friction coefficient, the decrease of kinetic friction coefficient with sliding velocity [24], or the variation of friction coefficient along the sliding surfaces. Moreover, a coupling between the normal and tangential motion can bring to dynamic instabilities even if the friction coefficient is maintained constant and no difference between the kinetic and the static friction is accounted for [25,26].

The work from Di Bartolomeo et al. [27,28] shows how the local ruptures at the interface (which arise at the local contact scale) are at the origin of the macro-slip recovered at scale of the system. The macro-slip, vice-versa, causes waves of relevant magnitude that diffuse until the boundaries of the mechanical system components, resulting in FIV. The presence of the waves that propagate into the bodies in contact influences the stresses and strains at the interface scale, triggering a mutual coupling

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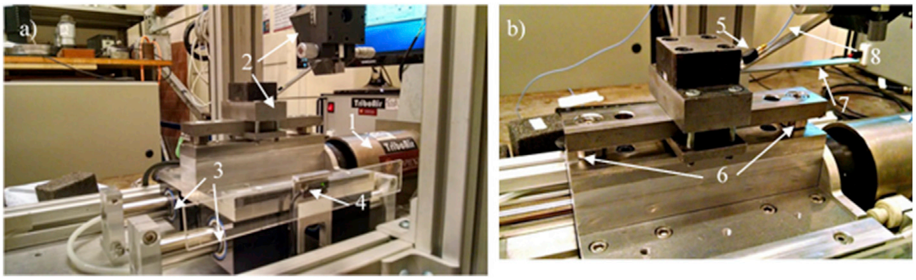

Fig. 1. a) experimental set-up: (1) voice coil, (2) clamping blocks, (3) air bushes, (4) linear optical encoder; b) magnification on the sliding beams, (5) accelerometer, 6) force transducers, (7) lower beam, (8) upper beam.

between local contact dynamics and system dynamics.

In this context, Adams [29] demonstrated that waves can propagate at the interface and generate local sliding conditions different from the global observed ones; besides, the apparent coefficient of friction (global) can be lower than the interface friction coefficient. Another interesting study on dynamic instabilities has been carried out by Tonazzi [30,31] who analysed the switch between different instability scenarios, from stick-slip to mode coupling.

Among the contact parameters which influence the contact dynamics, the surface roughness has been always one of the most interesting and difficult parameter to evaluate and, consequently, to simulate. One of the first works on the numerical approaches for rough surfaces was the research of Greenwood and Williamson [32], who simulated the presence of the surface roughness proposing a 2D model of two bodies in contact with a surface profile characterized by a normal distribution of summits with the same radius. From this first approach, a substantial amount of works continued on the same path, refining the characteristics of the contact, proposing multiasperity contacts [33,34], fractal model [35], until the reproduction of the real [36,37] topography of the surfaces. Moreover, a recent study [38] compares the Greenwood and Williamson theory [32] and the Persson theory [39], finding their range of validity in term of load-separation curves.

The reproduction of the surface topography is characterised by statistical surface descriptions bonded with asperity deformation models [40,41]; such approaches are therefore subjected to the presence of a refined mesh at the contact interface, usually involving high computational costs, especially for transient simulations. Because of the needed computational efforts, such approaches are limited to static or really short time simulations.

Considering the increasing need for transient simulations of frictional contacts and Friction Induced-Vibrations, this work is aimed to validate a newer friction law able to reproduce the broadband excitation coming from the contact excitation, by maintaining reduced computational costs. The work is based on the results and considerations of previous analyses [42], which reproduced experimentally the FIV and established the bonds between some contact parameters and the vibrational response of the dynamic system. A parametrical experimental campaign revealed the evolution of the system response with different sliding velocities and contact normal loads; different surface roughness have been tested, showing the influence of the surface topography in the system dynamic response. The objective of this paper is to validate the numerical friction law, introduced in Ref. [42], by comparison with experimental measurements on a simple frictional system. The numerical model has been first developed and the system dynamics has been investigated by a pre-stressed modal analysis. Then, the friction law with a perturbative term of the friction coefficient has been introduced into the numerical model for the transient simulations. The numerical approach has the objective to reproduce the broadband dynamic excitation coming from the contact, without reproducing the asperities distribution, with the aim to simulate the Friction-Induced Vibrations originated by a sliding contact between two rough surfaces. The identification of the stochastic term of friction by experiments, and its implementation into the friction law, will allow to account for its dynamic effects in stochastic structural dynamics modelling and in finite element modelling of frictional contacts.

The first section of the paper describes the dynamic frictional system that has been analysed both experimentally and numerically; in the second section the contact law is presented and, in particular, the choice of the perturbation term of the friction coefficient is described; the third section shows the results from the numerical simulations and the comparisons with the experimental results, which validate the numerical model. After the validation of the law for different surface roughness, the linear dependence with respect to the sliding velocity [42] is introduced too.

2. Dynamic frictional system

The frictional system has been chosen and designed to have a simple dynamics, in order to well discriminate its dynamic response by the broadband dynamic excitation from the contact. It is constituted by two steel beams in relative sliding contact. Furthermore, a simple system allows to better control the parameters such us the normal and tangential load, imposed relative velocity, contact area, etc. The dimensions of the beams have been set after a preliminary complex eigenvalue analysis, in order to avoid mode coupling instability, such that the system results in stable friction-induced vibrations.

The system has been reproduced both by an experimental set-up and a numerical model, with the same geometrical characteristics and boundary conditions.

In the following paragraphs, first the experimental set-up and an example of the results from the measurement campaigns are described; then, the numerical model is introduced together with an example of simulation results. The friction law used in paragraph 1.3 is the classical Coulomb law and it doesn't account for the contact dynamic excitation [42]. In the same paragraph, a comparison between the experimental and numerical results is proposed, highlighting the drawbacks of frictional numerical simulations due to the lack of local dynamic excitation at the contact.

2.1. Experimental set-up

Fig. 1a) shows the test bench TRIBOAIR, used for the reproduction of the relative motion under controlled loading conditions. The set-up has been built with the objective to reproduce and measure the Friction-Induced Vibrations during frictional contact, under well controlled boundary conditions.

On the test bench the two steel beams, in relative sliding contact, are mounted in clamped-free conditions, assured by the presence of massive blocks (2). An accelerometer (5) placed on the upper beam (8) measures the vibrational response of the system to the contact excitation (Fig. 1b).

The relative movement of the beams is allowed by an air bearing system (3) coupled with a linear voice coil (Gammatic LA15-65-000A), assuring the absence of unwanted source of friction, which could negatively influence the measures. The linear voice coil (1) allows for a planar controlled movement of the base, where the lower beam (7) is clamped. The velocity and position of the voice coil is determined by a controller