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Development of generalized Iwan model to simulate frictional contacts with variable normal loads

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ABSTRACT

Most friction models are originally proposed to predict restoring forces in mechanical contacts with constant normal load. In practice the contact interface kinematics may involve normal motion in addition to the tangential displacements, leading to variation of the contact normal load. This phenomenon is observed most strongly in contacts with high lateral vibration amplitudes and is known as slap. The current study establishes a general friction model to account for variation in the normal load and enables one to predict the behavior of a contact more precisely. Iwan model (1966) [5] is a suitable candidate for contact interface modeling and is able to represent the stick-micro/macro slip behavior involved in a friction contact. This physical based model is employed in the current work and its physical parameters are generalized to include the normal load variation effects. The model is characterized by a slippage distribution density function and a linear stiffness at stick state. Both these parameters, defined in presence of constant normal load in the original model, are derived considering normal load variation leading to generalization of the contact model. Conventional models with constant normal loads produce symmetric contact interface hysteresis loops, but the developed generalized Iwan model is capable of generating asymmetric hysteresis loops similar to those frequently seen in experiments. The generalized contact model is employed to simulate the measured behavior of a beam with frictional support observed in an experimental test set-up. The contact slippage distribution function is first identified in a constant normal load condition. Next in low levels of contact preloads where variation of the normal load is significant, the identified distribution function in generalized form is employed to predict the experimental observations.

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1. Introduction

Contact modeling is of considerable practical importance and occurs in many of mechanical systems. In recent decades, it has been the focus of a number of studies. Investigating the dynamic behavior of mechanical systems often requires modeling contact between two or more components of the system and using detailed finite element models is quite complicated and almost impossible to implement which generally leads to inaccurate predictions. In general, an experimental approach based on the identification of contact parameters appears to be more favorable because of its efficiency.

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Surface roughness has a key role on contact interface attributes and is responsible for nonlinear characteristics of the contact, which can change the dynamic behavior of the system in different vibration amplitudes. The interface is in stick regime at low vibration amplitudes, i.e. the system behaves linearly. As the response level increases, nonlinear mechanisms such as slippage and micro impact start to develop. Research works on contact friction characteristics have a rich history. Den Hartog [1] and Dowell [2] are the pioneers in this field followed by comprehensive investigations of friction phenomenon performed by Ferri [3] and Berger [4]. A large number of models have been developed to simulate the friction effects on mechanical systems. The Iwan model [5] is commonly used to model micro slip. It consists of networks of parallel Jenkin's elements allowing to model partial slip in the contact interface. There are other friction models offering smooth transition from stick to macro slip. The Dahl model [6], the Valanis model [7], the Leuven model [8,9] and LuGre friction model [10] are some examples. Gaul and Lenz [11] performed an experimental study to verify the capability of the Valanis model. Segalman [12] inspected the validity of the Iwan model experimentally. Gaul and Nitsche [13] performed a comprehensive overview on a range of constitutive models for contact interface mechanisms.

A contact model must be capable of taking into account the main nonlinear characteristics involved in the interface. Investigations on the contact dynamics are performed in three fields; the first is studying the friction characteristics in contact interface and only the tangential component of the contact force is considered and normal force assumed to be constant. All the mentioned models [1–13] fall in the first group. The application of these models is limited to contacts with simple geometry and negligible normal motion. In these models the coupling of normal motion and tangential vibration at the interfaces is ignored and the main outcome of this assumption is the symmetry of hysteresis loops. However in experimental observations asymmetric hysteresis loops are frequently seen indicating two returning curves of the hysteresis loops are not following the same trend. These different curves are the result of normal load variations. The second field of study is inspecting the behavior of interface in normal direction and considers a frictionless contact. The application of this approach is limited to collision of multi-body systems or contact with perfectly frictionless surfaces [14,15]. And the third field is developing a general contact model considering the interaction of normal and tangential vibration at the interface. Considering impact and friction in contact interface, Han and Gilmore [16] employed static and kinetic coefficients of friction to relate normal and tangential components of the contact force in their model. A general regularized contact model is developed by Gonthier et al. [17] which include normal compliance, energy dissipation and friction force using seven parameters. However these two models ignore the effect of normal load on tangential stiffness. Gaul and Mayer [18] used finite element approach to introduce an improved method to model contact interfaces. They adopted a nonlinear stiffness to model impact force between the contact surfaces. Yang et al. [19] employed Jenkins element to investigate the effect of normal load on hysteresis loop which only describes the full-slip or full-stick situation. In all published articles simplifications are used and to the authors knowledge there is no proper micro slip model capable of taking into account the effect of normal load variation to generate hysteresis loops observed in micro/macro slip region.

In this paper, a generalized Iwan model is developed. Original Iwan model is capable of reproducing the important contact properties as they are now understood and many authors used this model to predict contact behavior in structures. However the applications of Iwan model are restricted to cases with constant level of normal force. The physical based parametric Iwan model enables one to derive their characteristics directly from experimental data, and this is another reason for employing the model in this investigation. The model is generalized to include the effect of normal load variation in the contact. This is achieved by special scaling of the distribution function and the shear stiffness variations.

The remainder of this paper is organized as follows: in Section 2 the generated force by Iwan model in presence of normal load variation is obtained and properties of derived model are discussed. Sections 3 and 4 describe the mathematical modeling of set-up and the test procedure respectively. In Section 5, Iwan distribution function in high preload condition is identified. To ensure the validation of identified parameters two different identifications approaches based on the energy dissipation function and the force state mapping are employed. In Section 6 by reducing the preload, identified model is used to regenerate the measured data in variable preload.

2. Generalized Iwan contact model

Iwan's model composed of an infinite number of spring-slider arrays, shown in Fig. 1, known as Jenkins elements [5]. Jenkins element is an ideal elasto-plastic element, composed of a single discrete spring in series with a Coulomb damper with a critical slipping force. The Iwan model represents hysteretic features and models transitions in stick–slip states, which appears in a contact. Applied tangential forces to the model, distributes between Jenkins elements and obligate sliders with low critical slipping forces to begin to saturate and slip. This phenomenon known as micro-slip causes softening effect and energy dissipation at the contact interface. Increasing the applied force makes more sliders to slip, finally, at the "ultimate force" all dampers would saturate and the full contact's slip begins. Critical slipping force of frictional sliders f^* is shown by a distribution density function $\varphi(f^*)$, thus $\varphi(f^*)df^*$ is the fraction of sliders which their critical slipping force is between f^* and $f^* + df^*$.

A typical Iwan model force–displacement hysteresis loop is shown in Fig. 2. The force required for deformation along the path a–b, often referred to as "backbone curve", is:

$$f_{ab}(x) = \int_0^{kx} f^*\varphi(f^*)df^* + kx\int_{kx}^{\infty} \varphi(f^*)df^*, \tag{1}$$

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