Mechanical Systems and Signal Processing 103 (2018) 131–138

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Short communication

Reduced-order modeling approach for frictional stick-slip behaviors of joint interface

Wang Dong [a,b,*], Xu Chao [c], Fan Xuanhua [a], Wan Qiang [a]

[a] Institute of Systems Engineering, China Academy of Engineering Physics, Mianyang 621999, China
[b] Shock and Vibration of Engineering Materials and Structures Key Laboratory of Sichuan Province, Mianyang 621999, China
[c] School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China

ARTICLE INFO

Article history:
Received 8 November 2016
Received in revised form 25 September 2017
Accepted 1 October 2017

Keywords:
Stick-slip
Joint interface
Iwan model
Finite element method
Curve-fitting

ABSTRACT

The complex frictional stick-slip behaviors of mechanical joint interface have a great effect on the dynamic properties of assembled structures. In this paper, a reduced-order modeling approach based on the constitutive Iwan model is proposed to describe the stick-slip behaviors of joint interface. An improved Iwan model is developed to describe the non-zero residual stiffness at macro-slip regime and smooth transition of joint stiffness from micro-slip to macro-slip regime, and the power-law relationship of energy dissipation during the micro-slip regime. In allusion to these nonlinear behaviors, the finite element method is used to calculate the recycle force under monolithic loading and the energy dissipation per cycle under oscillatory loading. The proposed model is then used to predict the nonlinear stick-slip behaviors of joint interface by curve-fitting to the results of finite element analysis, and the results show good agreements with the finite element analysis. A comparison with the experiment results in literature is also made. The proposed model agrees very well with the experiment results.

1. Introduction

Modeling and simulation of joint interface are fundamental research domains in structural dynamics [1–3]. The existence of multi-scale, multi-physics and nonlinear behaviors of joint interface is mainly responsible for the complex dynamics of the assembled structures. Modeling for joint interface often takes a critical role in the design, control and optimization of many mechanical engineering systems [4].

Considering the micro-scale stick-slip behaviors of joint interface, the dynamic simulation of the assembled structure usually requires too many computing time steps [3]. One of practical methods to simulate the nonlinear behaviors is employing the reduced-order physics-based models instead of the joint interface of the build-up structure. With this method, developing the physics-based constitutive models for the joint interface is a preparation for the dynamic simulation and prediction. Modeling approaches for the stick-slip frictional behaviors of joint interface may be divided into two categories. On one hand, the approach combining the micro-scale contact mechanics with the statistical method is used to describe the stick-slip behaviors of rough surfaces [5–7]. On the other hand, based on the curve-fitting, the method combining the constitutive models with finite element analysis is used to describe the stick-slip behaviors [1,8–11]. In Ref. [11], the

* Corresponding author at: Institute of Systems Engineering, China Academy of Engineering Physics, Mianyang 621999, China.
E-mail address: king_east@sina.cn (D. Wang).

https://doi.org/10.1016/j.ymssp.2017.10.001
0888-3270/

stick-slip behaviors are described by force-displacement curves, which is responsible for the decrease of stiffness and increase of damping of mechanical structure.

The equivalent constitutive models should reproduce the typical nonlinear behaviors of joint interface [12,13]. Several appropriate contact models have been proposed to simulate the stick-slip behavior [9,11–14]. Most of these models are the so called stick-slip frictional ones, which allow partial slip in contact area of joint interface, such as Iwan model, LuGre bristle friction model, Dahl model and Valanis model. Compared with other constitutive partial slip models, Iwan model can describe the stick-slip behaviors of mechanical joint interface better. The parameters of Iwan model are almost physics-based. Therefore, the Iwan model has been widely adopted to simulate the partial-slip of joint interface by many researchers, such as Quinn [15], Deshmukh [16], Miller [17]. The Iwan model consisting of an array of parallel springs in series with sliders, called Jenkins elements [18,19].

The Iwan model with four-parameters was extracted to reproduce the stick-slip behaviors of lap-type joint by Segalman [3,9]. However, the stiffness smoothness of transition from partial slip to macro-slip suffers a sudden changing, and the model predicts no residual slipping stiffness at the macro-slip regime. To overcome this shortage, an modified Iwan model combining the an additional adjusted spring with Jenkins elements was proposed to exhibit the stick-slip characteristic of joint interface by Song and his coworkers [20,21]. The beam element with two adjusted Iwan models (normal direction and tangential direction) has been also developed to simulate the non-linear dynamic behaviors of jointed beam, which can be easily implemented with the finite element analysis. The method combining the Iwan model with the micro-contact mechanics of asperities was also adopted to construct the non-linear constitutive relation of bolted joints by Argatov [10], where the Masing's hypothesis was applied to calculate the energy dissipation. In Ref. [14], two main phenomena of mechanical joint interface are speculated with six parameters by Li. One of the phenomena is the residual stiffness during the macro-slip regime predicted by Song's model [21], the other one is the power-law relationship of energy dissipation during the micro-slip predicted by Segalman's model [9].

This paper attempts to develop a modified Iwan model which can describe the two phenomena induced by the stick-slip behaviors of joint interface. In this model, an additional adjusted spring was added to the parallel-series spring-sliders, with a power law distribution for critical sliding force is used. The proposed model can effectively predict non-zero residual stiffness of macro-slip regime, and can ensure the joint stiffness transition from micro-slip to macro-slip regime to be smooth by four parameters. The finite element method is used to analyze the nonlinear stick-slip behaviors of the lap-type joint interface. The proposed Iwan model is verified by fitting to the results of the finite element analysis and the experimental results in literature.

2. Constitutive models for joint interface

2.1. Iwan model

Fig.1a) shows the sketch map of lab-type joint interface and Iwan model. The partial-sliding behaviors of joint interface are modeled using the parallel-series Jenkins elements. As shown in Fig.1a), the upper moved part connected to a fixed part with several parallel-series Jenkins elements consisting of spring-slider unit, which are called Iwan model as shown in Fig.1b). Every Jenkins element has the same stiffness $k_i = k/n$ and a different critical sliding inception force q_i, $i = 1 \ldots n$. where n is the number of sliders, and k is the total of slipping stiffness. When the tangential load is small, most of sliders will keep stick, and only few of sliders, whose recycle force is larger than sliding inception q_i, will slip, this is called the micro-slip. With the increase of the tangential load, more and more sliders will start to slip till all sliders slip, this is called the macro-slip. Hence, the Iwan model can well model the partial slip behaviors of joint interface.

2.2. Modified Iwan model

A truncated power law distribution and a Dirac delta function of sliding inception force of Iwan model are used to yield the formulation of joint recycle force and energy dissipation per cycle by Segalman [9]. As shown in Fig. 1c), the method

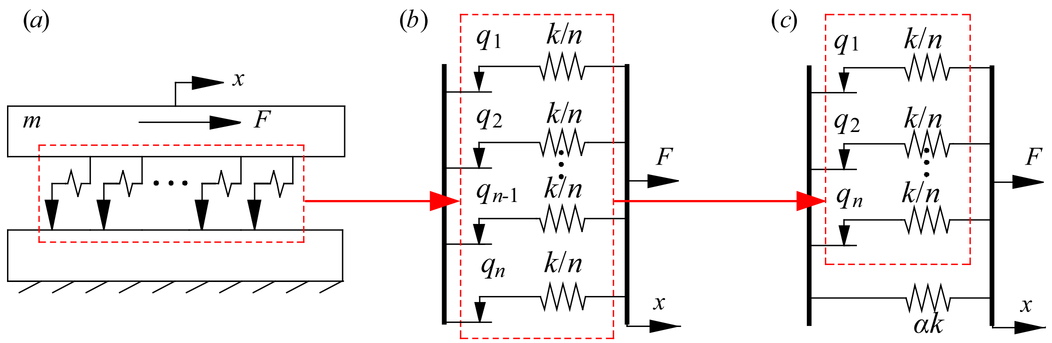

Fig. 1. Sketch map of lab-type joint and Iwan model: (a) lab-type joint interface, (b) Iwan model, (c) modified Iwan model.