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# A six-parameter Iwan model and its application

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ABSTRACT

Iwan model is a practical tool to describe the constitutive behaviors of joints. In this paper, a six-parameter Iwan model based on a truncated power-law distribution with two Dirac delta functions is proposed, which gives a more comprehensive description of joints than the previous Iwan models. Its analytical expressions including backbone curve, unloading curves and energy dissipation are deduced. Parameter identification procedures and the discretization method are also provided. A model application based on Segalman et al.'s experiment works with bolted joints is carried out. Simulation effects of different numbers of Jenkins elements are discussed. The results indicate that the six-parameter Iwan model can be used to accurately reproduce the experimental phenomena of joints.


## 1. Introduction

Engineering systems are commonly assembled using various joining techniques, such as bolting, clamping, riveting etc. Mechanisms including micro-slip and macro-slip on the contact interfaces of joints are responsible for stiffness nonlinearity, energy dissipation and vibration damping of the built-up structures [1–4]. Damping resulting from joints can account for as much as 90% of the total [5]. Limitations of calculation scales and explicit time steps make direct numerical simulation (DNS) impractical in the dynamic analysis of built-up structures. For instance, a jet engine with hundreds of joints may have the length scale of meters, while for those elements describing micro-slip behaviors that would be on the order of $10^{-5}$ m to capture kinematics of the components. On the other hand, calculating till steady state would lead to a response period on the order of seconds, while the explicit time step of the problem would be on the order of nanoseconds. With these two multi-scale limitations, calculation of this problem becomes intractable. Thus, developing reduced order constitutive models that accommodate the nonlinear properties of joints is of great value.

Descriptions of contact interface modeling have been introduced by many researchers. Among the works reviewed by Ferri [6], Gaul and Nitsche [7] and Berger [8], Iwan model [9] shows the potentials for constitutive modeling of joints. It consists of spring-slider units, which are also referred to as the Jenkins elements, arranged either in parallel-series or series–series system as shown in Fig. 1.

Iwan model was first developed for the purpose of describing elasto-plastic behavior of metals [10]. The initial work of applying parallel-series Iwan model to describe the mechanisms of joints was presented by Segalman [11]. Iwan [9] provided a uniform density function as the distribution function, which was followed by Song et al., Shiryayev et al. and Zhang et al. Experimental phenomenon observed by Gaul and Lenz [12] indicated that a joint possesses residual stiffness during macro-slip. In order to address this phenomenon, Song et al. [13] demonstrated an adjusted Iwan model by applying an additional elastic spring in the parallel-series Iwan model. Shiryayev et al. [14] presented an approach of parameter estimation for Song et al.'s model. The analytical expressions of Iwan model based on the uniform density function indicated

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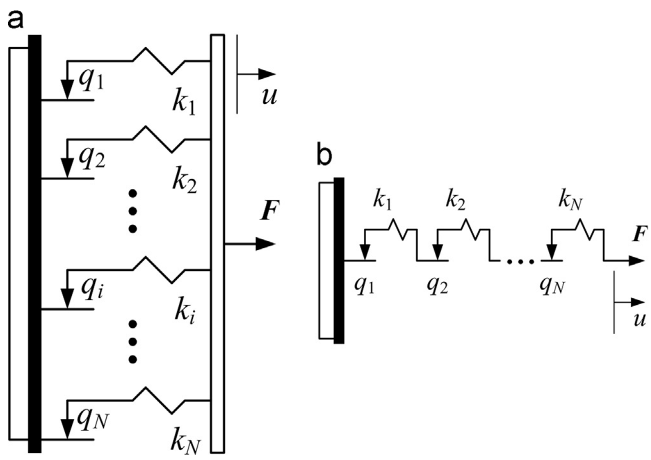


**Fig. 1.** Schematic of two different types of Iwan models (a) Parallel-series; (b) Series–series.

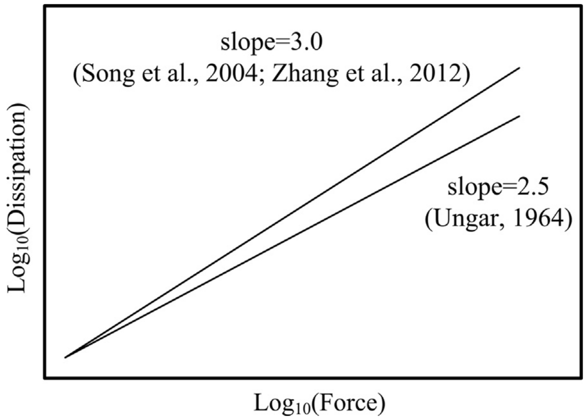


**Fig. 2.** Plots of the power-law relationships between energy dissipation and force amplitude.

that the theoretical power-law relationship of energy dissipation is 3.0 [15]. Though this theoretical value could reflect the phenomena of energy dissipation, it cannot precisely describe the experiment results [16] as shown in Fig. 2. In order to precisely describe Ungar's experimental work, Segalman [17] provided another distribution function with four parameters and proposed the four-parameter Iwan model.

A series–series Iwan model was developed by Quinn and Segalman [18] to simulate the contact interface between a rod and a frictional foundation. Motivated by the series–series Iwan model, Miller and Quinn [19] proposed a model with a two-sided interface for describing the structure damping caused by joints. Deshmukh et al. [20] developed a new Iwan element and proposed a shear-lag model to simulate interface sliding behaviors. In recent studies the parallel-series Iwan model was more frequently used. Segalman and Starr [21,22] showed that any material or structural model that satisfies Masing's hypothesis can be expressed as a unique parallel-series Iwan model. Argatov and Butcher [23] also stressed the applicability of parallel-series Iwan model.

According to the experimental works of Ungar, Gaul and Lenz and Segalman et al. [24], two main phenomena can be concluded. 1. There exists residual stiffness on joint contact interface during macro-slip; 2. The power-law relationship of energy dissipation during micro-slip is between 2.5 to 3.0, rather than 3.0. Song et al. and Zhang et al.'s model based on the uniform density function is only capable of reproducing the first phenomenon while Segalman's model can only be used to reproduce the second one.

This paper aims to develop a six-parameter, parallel-series Iwan model that is capable of describing those two main phenomena of joints. In Section 2, a six-parameter Iwan model based on a truncated power-law distribution with two Dirac delta functions is proposed. Also in this section the analytical expressions of force–displacement and dissipation–displacement relationships associated with the model are deduced. Section 3 demonstrates the parameters identification procedure. In Section 4, the discretization method of the identified Iwan model is proposed. A model application based on Segalman et al.'s experiment is provided in Section 5. Finally, conclusions and summaries of this paper are made in Section 6.

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