On the effects of meso-scale friction interface geometry on nonlinear dynamics of large mechanical structures

Jie Yuan*, Loic Salles† and Christoph Schwingshackl ‡
*Aerospace Centre of Excellence, University of Strathclyde, Glasgow, G1 1XQ, UK
†Skolkovo Institute of Science and Technology,Bol'shoy Bul'var, 30, Moscow, Russia, 121205
‡Vibration University Technology Centre, Imperial College London SW7 2AZ, London,UK

Summary. Friction interfaces can be almost found in all engineering structures which has major influence on their dynamical response. Previous experiments found that mesoscale geometrical characteristics of friction interfaces have a significant impact on the nonlinear modal properties of assembled systems but their effects on nonlinear dynamics has not numerically explored due to the complex coupling between tribology and dynamics. This work proposes an efficient multi-scale approach to investigate the influence of meso-scale interface geometry of friction interfaces. It is applied to a realistic "Dogbone" test rig designed to assess the effects of aero-engine blade root geometries in a fan blade system. The friction interface with different meso-scale profiles are effectively investigated.

Introduction

Friction interfaces have been widely used in assembled structures to connect components and transfer the mechanical loads. They are regarded as the main source of nonlinearities and uncertainties in an assembled structure. The relative motion occurring on friction interfaces often leads to a significant change of its dynamics such as reducing overall stiffness, shifting resonance frequencies and decreasing vibration amplitude through strong energy dissipation. A number of experiments have shown that the nonlinear dynamical behavior of the system is very sensitive to the geometry of friction interfaces [1, 2], which can greatly change the static and dynamic properties such as with crowning interface geometries. However, the effects of meso scale interface geometry on nonlinear dynamics has not been much investigated. However, there is a lack of efficient numerical approaches to design and analyse the influence of such meso-scale interface geometries on the nonlinear dynamical properties.

Methodology

This work proposes a multi-scale modelling framework to study the effects of meso-scale interface geometries on the nonlinear dynamics of complex dynamical systems with friction interfaces. The approach mainly consists in the integration of micro/meso-scale friction interfaces into macro-scale FE model. As shown in Eq.1, nonlinear static analysis (with a flat-on-flat contact interface) is firstly performed to evaluate overall contact loads on the friction interfaces under different pre-loadings. Then, based on overall contact loads from the nonlinear static analysis, a highly efficient semi-analytical solver based on the boundary element method shown in Eq.2 and 3 is performed to obtain the pressure and gap distribution from the contact interface with different geometrical characteristics [3]. The static pressure and gap distribution are then used as the input for a frequency domain nonlinear vibration solver to evaluate nonlinear vibration response of the whole assembled structures where the governing equation is shown in Eq.4. The detailed methodology for nonlinear dynamic analysis can refer to [4].

$$\mathbf{K}\,u(t) + \mathrm{F}_{nl}(u(t)) = \mathrm{F}_s(t) \tag{1}$$

$$u_z(x,y) = \frac{1-\nu^2}{\pi E} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \frac{p(\xi,\eta)}{\sqrt{(\xi-x)^2+(\eta-y)^2}} d\xi d\eta \tag{2}$$

$$u_z(i,j) = K_{zz} \otimes p = \sum_{k=1}^{N_x}\sum_{l=1}^{N_y} p(k,l) K_{zz}(i-k, j-l) \tag{3}$$

$$\mathbf{M}\,\ddot{u}(t) + \mathbf{C}\,\dot{u}(t) + \mathbf{K}\,u(t) + \mathrm{F}_{nl}(u(t)) = \mathrm{F}_e(\gamma, \varphi, \Omega, t) \tag{4}$$

Test case and results

The test case for this study is based on a fan blade root test rig setup as shown in Fig.1 (a). The "Dogbone" rig consists of two main components: a set of identical solid root-block disks and a set of "bones" for different root designs [5]. Fig.1(b) shows the FE model representing the test rig which is performed in Hypermesh where matching mesh has been used on four friction interfaces. The 3D node to node contact element as shown in Figure 1(c) has been used to simulate the contact force. Different meso-scale interface geometries are considered including the different interface shapes including central bump, Y wise bump, edge wise radium. The geometry of the central bump is constructed using defined ellipse curves in both directions with maximum height in the central point similar to [2]. Figure 2 (a) shows the pressure distribution of the central bump contact interface with different maximum heights. With the increase of bumpiness of central bumper,

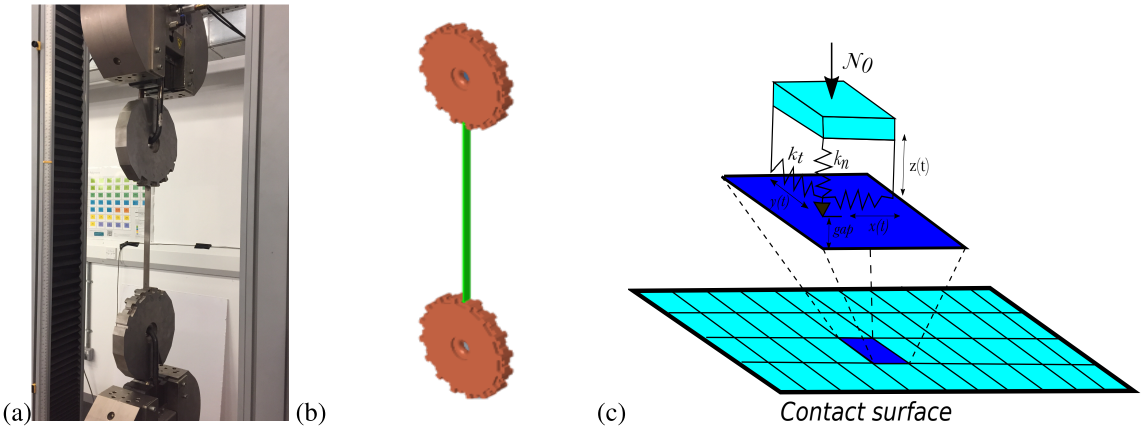

Figure 1: (a) Dogbone Test rig setup; (b) FE model of the Dogbone rig (c) Contact friction element

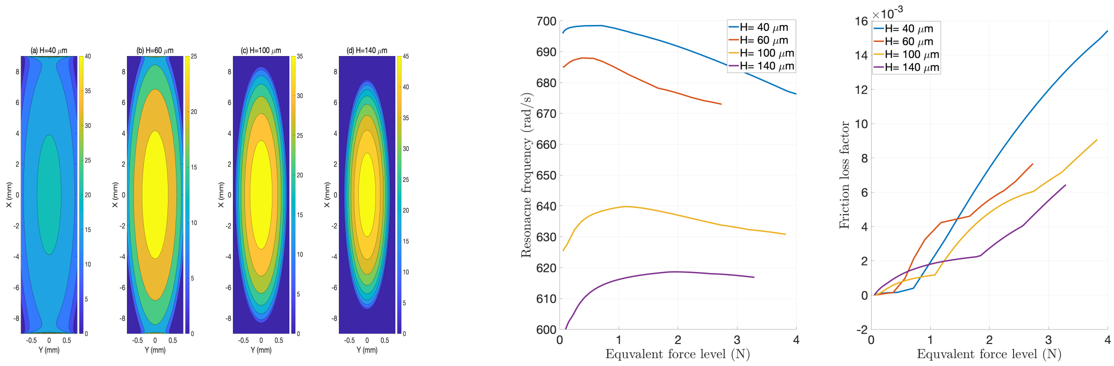

Figure 2: (a)Normal contact pressure and (b)Nonlinear modal properties of the Central Bump for diffident levels of bumpiness

the pressure distribution becomes more centralized in middle of the contact interface with higher stress amplitude. Figure 2 (b) shows the nonlinear modal properties of these central bump contact interfaces at different force levels. With the increasing bumpiness, it shows the stating resonance frequency is reduced from 700 to 600 rad/s mainly because of the increasingly reduced contact area making jointed friction interfaces become less and less stiff. With the increase of force level, for all the cases, the resonance frequency increases initially and then gradually decreases with further increase of energy levels.

Conclusions

This work presents a multi-scale-based approach to efficiently evaluate the effects of meso-scale interface geometries on the nonlinear dynamical response of structures with frictional interfaces. The proposed approach was applied to design and analysis of a blade root Dogbone test rig (similar to fan blade dovetail joints) to evaluate the effects of blade root geometries on the overall dynamic response of the system. Different meso-scale interface profiles including different shapes, level of bumpiness and edge radium were investigated. The studies show the proposed multi-scale approach can efficiently evaluate the influence of meso-scale interface profiles on the contact pressures at a much lower cost. The effects of meso-scale interface profiles on the damping and resonant frequency behavior are significant which should not be ignored in the design and analysis of jointed structures. The developed tool can also be used to design and optimize the friction interface for improved nonlinear dynamics.

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