Interaction between vibration and friction of Coulomb friction contact surfaces

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Abstract

Contact surfaces with dry Coulomb friction are present in many engineering structures. A two dimensional model of these systems in the form of a block-incline is proposed. Its behaviour under harmonic excitation is investigated using finite element method (FEM) with an explicit solver. It was found that the interaction between vibration and friction depends on the state of vibration amplitude and frequency of the harmonic excitation, and on the level of preloading force. The mode of interaction can be classified into three main regions: no change, the block moves up the incline and the block moves down the incline, with mixed modes in the border areas between these domains. The results found by the FEM simulation agree well with previous experimental findings.

Keywords: Coulomb friction, nonlinearity, finite element, explicit solver, thread loosening, squeal.

1 Introduction

Friction is present in many engineering systems. It may be viewed as a nuisance responsible for dissipation of energy and many efforts have been devoted to minimise it. In many other instances friction is exploited for the service of mankind, such as in braking systems, in assembling components using rivets or bolt and nuts, in vibration control of turbine blades [1]. When such systems are subjected to dynamic loading, the interaction between vibration and dry friction is a highly non-linear problem. It is well known that under dynamic loading, threaded fasteners can become loosened leading to malfunctioning, costly maintenance or even catastrophic failures of systems in automotive, aeronautical and electronic industries. Railway lines are laid on sleepers which in turn rest on a foundation of ballast consisting of crushed hard rocks. At very high train speeds, it has been found that dynamic vibrations can set the ballast in motion and the rock ballast offers meek resistance to the dynamic load resulting in fast sinking of the railway lines which can lead to derailing [2, 3]. These failures can be attributed to vibration induced loss of contact of friction surfaces. This takes place when the friction forces that exist between surfaces are eliminated in the course of interaction between friction and vibration. This loss of friction has been accepted as causing threaded fasteners loosening of bolted assemblies and has prompted experimental efforts in the last sixty years, mainly in USA to understand the phenomenon and to prevent vibration induced bolt loosening [4]. The recent works by Hess and associates [5, 6] gave good agreement between an analytical rigid body model and experimental results. FEM modelling, treating the system as deformable bodies, has also been used to investigate the threaded fastener loosening [7, 8]. The research over the last sixty two years have shown that because the problem is non-linear and involves many parameters [9], conclusive agreement among researchers has yet to be reached. Threaded fasteners are actually three dimensional surfaces in contact under dry friction and preloaded by initial tightening torque, they are subject to wear and manufacturing inaccuracy, and due to the effect of stress concentration most of the load is taken by a few threads. However it has been popular in engineering mechanics to assume that contact is intimate and the load is equally shared between many threads. This simplification leads to an equivalent two dimensional model of block-incline obtained by developing the thread surfaces with that of the bolt as the incline and that of the nut as the block. Most researchers assume both the block and incline are rigid bodies and ignore their deformability. In the railway ballast, the crushed rocks are polyhedral bodies coming into contact on many surfaces due to mainly compacting load and gravity. They are compacted firstly by the mere pouring process, followed by tamping processes and by working load due to the moving trains. The ballast system can also be simplified as a two-dimensional model with relatively loose rocks as deformable polygons and densely compacted rocks as a deformable incline body. Such a simple two dimensional model taking into account the deformability in the form of a block-incline system was proposed in [10] and studied by both experiments and FEM in order to focus on a number of fundamental parameters. The experimental set up is shown in Figure 1, with the harmonic excitation on the block and incline model imparted by a shaker. Accelerometers were attached to both the incline and the block.
Preloading was effected by using up to 11 small rare earth magnets inserted into holes which had been countersunk into the base of the block. The arrangement allows the preloading to be varied by changing the number of magnets while ensuring a symmetrical pattern to create uniform distribution of magnetic flux over the block base. Three levels of preload were used: minimum, medium and maximum preload corresponding to 6, 13 and 23 Newtons respectively.

In a static state, the angle of inclination and the coefficient of friction are two important factors determining whether the block would be stationary or slide down the incline. However the behaviour of the system is far more interesting when dynamic load is involved. It was found that when the system is excited by harmonic vibration, the interaction between Coulomb dry friction and vibration on the behaviour of the block-incline system is manifested in one of three scenarios: the block is stationary with respect to the incline, i.e. they are always in intimate contact (termed as no change); the block moves up the incline (moving-up); and the block moves down the incline (moving-down). The latter two cases imply that there must be instances of separation between two surfaces. It was found that the mode of interaction depends on the amount of preload, harmonic excitation amplitude measured in G and its frequency of vibration (Hz). For a given preload, these states of vibration amplitude and frequency of harmonic excitation form regions of behavioural mode of interaction. The FEM simulation using implicit solver and Newton-Raphson method [10] correlated well with experimental results, however it requires extensive computing resources and it is difficult to obtain convergence. In this paper, the behaviour is investigated by FEM modelling using an explicit solver.

2 Block-incline model under harmonic vibration by explicit FEM modeling

The block and incline system was modeled by FEM (Figure 2) by plane stress elements, with contact elements between the block and incline surface. Harmonic vibration excitation at a specified vibration amplitude of acceleration and frequency was imparted to the system at the base of the incline.

Besides gravity force, the preloading used in experiments [10] was modeled by uniform pressure on the block. The shaker was modeled by soft structural elements. FEM Explicit modeling permits very fine sweeping of frequency and amplitudes over a larger range than possible with experiments or FEM Implicit modeling in [10]. The vibration process can be inspected frame by frame or by animation to determine whether there is any separation between block and incline surface (Figure 3). Displacements for initially coincident block-incline pairs of nodes were processed to give the relative...
velocity components: UX for tangential component (along the incline surface), UY for normal component. These can be transformed by Fast Fourier Transform (FFT) to display the distribution in frequency domain. First the preloading pressure on the block was kept constant. The frequency and amplitude of harmonic vibration were then swept between 50-500 Hz and 0.5-80 Gs respectively. For each simulation the interaction mode was observed to see whether there is any separation or whether the block is in intimate contact with the incline, moving-up, or moving-down.

Figure 3: Displacement after 0.3 s showing the block is separated from the incline

Interaction mode between block and incline for Preload of 23 N

Figure 4: Different regions of interaction modes at fixed preloading force of 23 N

The results found by FEM simulation agrees well with experimental observations in [10] with more refined simulations made possible by FEM along borders between these regions. It can be seen from Figure 4 that the interaction mode of the block-incline system under harmonic vibration depends on the state of frequency and amplitude of vibration for a given amount of preloading. For preload of 23 N, at low vibration amplitude (typically below 3G) the block is always in intimate contact with the incline for all frequencies. For frequencies above 200 Hz and above 3G, the block moves down incline, while for frequencies below 200 Hz and above 5G, the block moves up the incline against gravity. In moving up or down the incline, the block must have been intermittently knocked upwards, then falling down under the effect of gravity and impacting the incline again. Mixed mode (white areas) with the block initially moving up but eventually moving down the incline, is observed in the border regions. The mode reflects the power play between inertia loads due to harmonic excitation, the tangential component of which may be up or down, contact forces and compression preload. The border regions are where the random nature of separation and impact may assist or oppose one side against the other in the struggle for dominance.
Typical variation of UX and UY with time is shown in Figure 5. Note that UY is relatively much smaller than UX and the variation of UY clearly shows the intermittent clattering between the block and incline. Effects of various levels of vibration amplitude for fixed preload and frequency are shown in Figures 6, 7. Figure 6 clearly shows that the interaction mode changes with the level of vibration amplitude.

Figure 5: Time variation of relative velocity components UX and UY of block to incline for harmonic excitation of 5G, 500 Hz at preload of 23 N.

Figure 6: UX for 23 N preload and harmonic excitation at 500 Hz at various vibration amplitudes

Figure 7: UY for 23 N preload and harmonic excitation at 500 Hz at various vibration amplitudes
Next the effect of preloading on the interaction behaviour of the block-incline system is investigated for a given set of amplitude vibration (2G) and frequency (50 Hz). Low frequency of 50 Hz was chosen as the behaviour with respect to various vibration amplitudes is more complex in the low frequency region. The results are shown in Figure 8.

Figure 8 indicates that changing preload can change the mode of interaction as expected: at high preload the block remains essentially in intimate contact with the block; if preload is reduced separation of the block and incline will incur; for medium preload the block can move up the incline but if the preload is further reduced the tendency is moving down the plane.

The simulation was then extended to other levels of vibration amplitudes. FEM modeling permits simulation at finer resolution of vibration amplitude than experimental settings of [10]. The effect of preload at three settings of preload in [10] on the interaction mode is shown in Table 1.

Table 1: Effects of preload on the interaction of the block-incline system for simulation time of 0.5 seconds

<table>
<thead>
<tr>
<th>Vibration Amplitude (G)</th>
<th>6 N preload</th>
<th>13 N preload</th>
<th>23 N preload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No change</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>1.5</td>
<td>No change</td>
<td>Moving down</td>
<td>No change</td>
</tr>
<tr>
<td>2</td>
<td>No change</td>
<td>Moving up</td>
<td>No change</td>
</tr>
<tr>
<td>2.5</td>
<td>Moving down</td>
<td>Moving up</td>
<td>Moving up</td>
</tr>
<tr>
<td>3</td>
<td>Moving down</td>
<td>Alternating moving up then down</td>
<td>Moving up</td>
</tr>
<tr>
<td>4</td>
<td>Alternating moving up then down</td>
<td>Up for 0.05 s then down</td>
<td>Moving up</td>
</tr>
<tr>
<td>5</td>
<td>Alternating moving up then down</td>
<td>Up for 0.07 s then down</td>
<td>Moving up</td>
</tr>
<tr>
<td>7</td>
<td>Up for 0.04 s then down</td>
<td>Moving up</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Up for 0.15 s then down</td>
<td>Up for 0.14 s then down</td>
<td>Moving up</td>
</tr>
<tr>
<td>20</td>
<td>Up 0.4 s then down</td>
<td>Up for 0.06 s then down</td>
<td>Moving up</td>
</tr>
<tr>
<td>40</td>
<td>Up violently</td>
<td>Moving up</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen that FEM simulation allows a closer look at the borders between regions shown in Figure 4. Furthermore experimental observations probably could not detect the initial small moving up of the block over a very short time. As expected in the border region, the behaviour can be a mixed mode of alternating moving ups and moving downs. Obviously for the same frequency and vibration amplitude, the amount of preload influences which mode the system would settle down to. For example at 3G, 50 Hz the block would move down for 6 N preload, move up for 23 N preload, and moves alternatively up and down for the case of 13 N preload.
3 Conclusions

FEM modelling of the two dimensional model of the block-incline can be used to investigate the effects of the most important parameters on the dynamic behaviour of contact surfaces with Coulomb dry friction: vibration amplitude and frequency of harmonic excitation, preloading force, angle of inclination and coefficient of friction. It takes into account deformation of both the block and incline, stress wave and intermittent impacts between the two bodies. It was found that the system behaves in a very intriguing manner when subjected to harmonic vibration excitation. The interaction under harmonic excitation is represented by three domains of behaviour depending on the combination of amplitude of vibration and frequency of harmonic excitation and the amount of preloading: a domain of no change or intimate contact for low vibration amplitudes. The other two domains involve intermittent separation of the two surfaces: one domain with the block move up the incline plane, mainly for high vibration amplitude and low frequencies, the other for high vibration amplitude and high frequencies with the block move down the incline plane. In systems relying on contact and friction force such as threaded fasteners, the “moving down” region reflects a breakdown of the system which may lead to functional or catastrophic failure. The possibility of using the region of “moving up” against gravity for bolt tightening and handling material up an incline without using moving conveyor belts is very interesting. These findings agree well with experimental results presented in [10]. Furthermore, the FEM modelling using explicit solver here can investigate more thoroughly the regions bordering the three domains, especially the behaviour in the initial short duration of time during which the initial movement of the block was found to be moving up even it eventually moves down the incline. This model has been extended to study the reported phenomenon of “liquefaction” of railway ballast for very fast trains [11] and train brake squeal [12].

4 References


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