laptop computers or even virtual reality environments running either Windows XP or Linux-based systems.

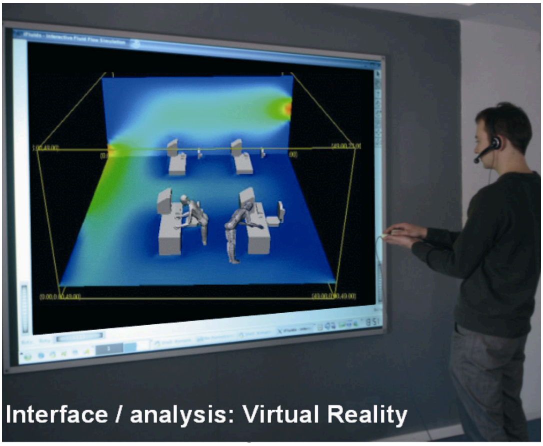

Figure 2: Visualization and steering front-end run on a Linux workstation

By displaying the results together with the original geometry, the application offers an intuitive way of exploring the results (see Figure 2). The interaction with the objects is implemented using draggers for both the visualization of the results and representation of the geometry. These draggers allow the objects to be moved, scaled and rotated. It is possible to load new objects or delete objects during run-time (see [1] and [10]). Boundary conditions, such as the temperature or the inflow velocity, can either be specified in the geometry file or may be edited interactively using a dialog window (see Figure 3). The boundary condition information is stored together with the original (facetted) geometry. Changes have impact on the original geometry data, as loaded into the CSE. Information on boundary conditions, as defined for the geometry, is thereby independent from the applied simulation kernel. Each time changes are made to an object, data is sent to the simulation kernel and the grid is regenerated.

Besides the mentioned stand-alone application of the CSE, a cooperative version (see [1]) is available, in which visualization clients share the same geometry database and work together on a project. Clients may be attached and detached during simulation. It is even possible to use different simulation cores or to visualize data from the same computation on each client application in different ways.

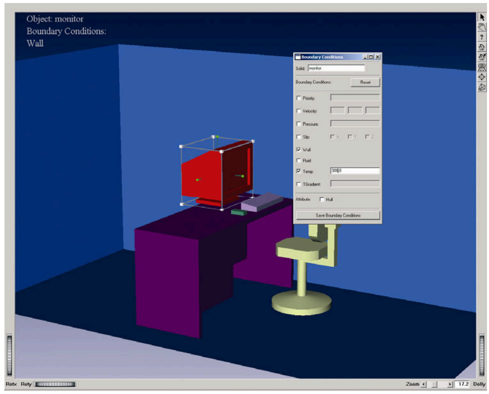

Figure 3: Modification of boundary conditions during run-time using a dialog box

The visualization and steering clients connect to a common, so-called "GeomServer" which holds the geometry information, coordinates the changes to the model and locks an object for other users while a designated user makes changes. While the communication in the stand-alone application is based on MPI for both the parallelized CFD core and between computation and visualization, the communication in the cooperative version between the client, the "GeomServer" and the simulation servers is based on the Orbacus CORBA library (see [7]). Another advantage of using CORBA-based communication is that the GeomServer, the visualization and steering clients as well as the simulation servers may be executed on different hardware platforms without the need for special MPI implementations such as PACX-MPI.

Implementation in a sample VR environment

As part of a research project, we implemented a special version of the CSE to meet the needs of our industrial partner Siemens AG (Corporate Technology) when it comes to presenting results to customers.

The VR room of the participating department of Siemens AG is equipped with a passive stereo setup complete with standard hardware. The whole screen is subdivided into three smaller sub-screens (see Figure 4). Each of these sub-screens has two projectors with polarization filters for the right and the left channel, respectively. The system is built as a visualization cluster, i.e. each projector is directly connected with a visualization computer. Therefore, not only the different views but also the right and left-hand channel of a scene visualized in stereo mode have to be rendered on different computers that need to be synchronized accordingly. In addition, a separate computer for handling the presentation and controlling the individual clients of the visualization cluster is also installed.

The visualization and steering application is started on the master machine in non-stereo mode and all of the menus and messages of the CSE appear on this node in an exclusive manner. This means that these menus do not interfere with the stereo impression, as seen by the audience. The camera positions for the stereo projection on the VR screen are controlled by the master application, i.e. if the person giving the presentation rotates the scene, or if it is zooming in or out, the view as produced by the visualization cluster for the 3D screen follows instantaneously.

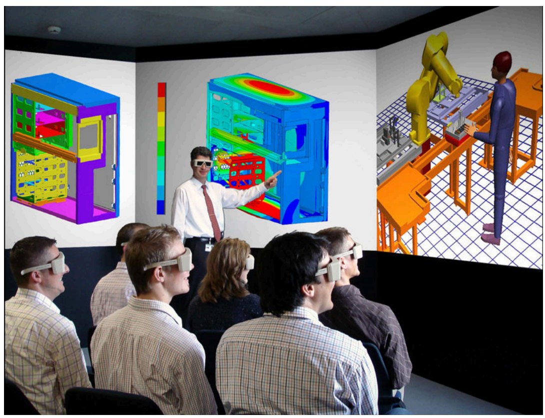

Figure 4: Screen arrangement in a VR room (courtesy of Siemens AG, Corporate Technology)

Unfortunately, the set-up described above is not directly supported by the visualization library used in the CSE. Based on the cooperative version of the CSE, we implemented our own stereo viewing mode, where each machine runs the same visualization and steering client program. Certain flags in a configuration file determine the mode in which the client starts and which configuration values are to be used for the stereo viewing. The values passed to the visualization determine the camera offset, among several other parameters, between the right and left-hand channel and accordingly determine the stereo impression.

The server that handles all the geometry and collaborative information, the "GeomServer", has been extended to include information on the camera position etc. If a visualization client is started as a visualization slave and connects to the "GeomServer", it becomes remotely controlled by the master client. All the changes made to the view of the scene on the master client are distributed straight away to all the connected slave nodes via the "GeomServer".

Here again, the simulation kernel runs on a standard Linux-based cluster, for example. It distributes results to both the master and the slave nodes via the CORBA-based simulation server, as described above. Compared to the version in the original collaborative CSE, no changes to the simulation server have been necessary.

In order to use the visualization client for data produced in a non-interactive way by other CFD packages, we intend to implement an interface for reading those datasets and sending them to the visualization engine.

Application

As indicated in the first section, the range of applications is quite large: from office space to machinery rooms or from cars to carriages and airplane cabins. Due to computer resources, the results of an interactive simulation with a limited resolution can be used to improve the model. An optimized configuration may be posted as a batch job at a higher resolution. By way of an example, we present the model of a train carriage with the simulation of free convection-type flow (in cooperation with Siemens AG, Corporate Technology), (see Figure 5). The buoyant forces result from heaters placed under the seats. With 40 million degrees of freedom the model is still comparatively coarse. It was computed on a Linux cluster within a few hours computing time. The grid generation process took only about 1.5 seconds on a single PC.

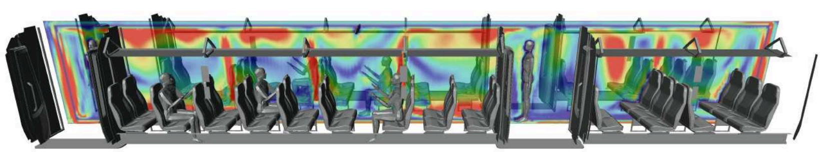

Figure 5: Turbulent convection in a passenger train cabin. Visualization of the average velocity field. Red (blue) colors indicate high (low) flow velocities.

Acknowledgements

The authors are grateful to the Bayerische Forschungsstiftung (Munich, Germany), KONWIHR (Competence Network for Technical High Performance Computing in Bavaria, Germany) and to Siemens AG, Corporate Technology for their financial support. Part of this work is being sponsored by grant No. AZ 630/04 awarded by the Bayerische Forschungsstiftung. Other partners in this project are the Fraunhofer Institute for Building Physics (Holzkirchen, Germany), the companies Mueller-BBM (Planegg, Germany) and Siemens AG (CT, Munich, Germany) as well as the Leibniz Computing Centre of the Bavarian Academy of Sciences and Humanities (Garching, Germany).

Bibliography

[1] Borrmann A., Wenisch P., van Treeck C., Rank E.: Collaborative computational steering: Principles and application in HVAC layout, Integrated Computer-Aided Engineering (ICAE), vol. 13(4): 361-376, 2006.

[2] d'Humières D., Ginzburg I., Krafczyk M., Lallemand P., Luo L.-S.: Multiple-relaxation-time lattice Boltzmann models in three dimensions, Phil. Trans. R. Soc. Lond. A, 360, 437-451, 2002.
[3] Krafczyk M., Tölke J., Luo L.-S.: Large-eddy simulations with a multiple-relaxation-time LBE-model, Int. J. Modern Physics B, 17:33-39, 2003.
[4] Lallemand P., Luo L.-S.: Theory of the lattice Boltzmann method: Acoustic and thermal properties in two and three dimensions, Phys. Rev. E, 68, 036706, 2003.
[5] Mezrhab, A., Bouzidi, M. and Lallemand, P.: Hybrid lattice-Boltzmann finite-difference simulation of convective flows, Computers and Fluids, 33, 623–641, 2004.
[6] Mercury OpenInventor Bibliothek, http://www.tgs.com, 2006.
[7] Orbacus CORBA library, http://www.orbacus.com, 2006
[8] van Treeck C.: Gebäudemodell-basierte Simulation von Raumluftströmungen. Dissertation, TU München, Shaker Verlag, ISBN: 3-8322-3375-X, 2004.
[9] van Treeck C., Rank E., Krafczyk M., Tölke J., Nachtwey B.: Extension of a hybrid thermal LBE scheme for Large-Eddy simulations of turbulent convective flows, Computers and Fluids, 35: 863-871, Elsevier, 2006.
[10] van Treeck C., Rank E.: ComfSim - Interaktive Strömungssimulation und lokale Komfortanalyse in Innenräumen. In: Bayerische Forschungsstiftung (Ed.), Annual Report (Jahresbericht) 2005, 66, Munich.
[11] Wenisch P., van Treeck C., Borrmann A., Rank E., Wenisch O.: Computational steering on distributed systems: Indoor comfort simulation as a case study of interactive CFD on supercomputers, Int. J. Parallel, Emergent and Distributed Systems, accepted for publication, 2006.
[12] Wenisch, P. and Wenisch, O.: Fast octree-based Voxelisation of 3D Boundary Representation-Objects, Technical report, Lehrstuhl für Bauinformatik, Technische Universität München, 2004

Dynamic Load Effects on Coulomb Friction Contact Surfaces

Danh Tran [1]
[1] School of Architectural, Civil and Mechanical Engineering, Victoria University, P.O. Box 14428, MCMC 14428, Australia, PH (613)9919- 4227, FAX (613)9919-4139, email: Danh.Tran@vu.edu.au

Abstract

Engineering systems of deformable bodies held together by dry friction, gravity and preload can be found in many engineering applications such as the railway ballast, structures connected by bolts and rivets. This paper studies the behavior of a two dimensional model of deformable block-incline system under dynamic loading of harmonic vibration by using finite element modeling and by experiments. It was found that the integrity of the system can break down, and that there are three regions of no relative movement between the block and the incline, the block moves down the incline and the block moves up the incline, depending on the value of excitation parameters of harmonic acceleration amplitude, frequency and the amount of preload between the two surfaces.

1. Introduction

Friction is present in many engineering systems. It is usually viewed as an accepted fact of life or a nuisance responsible for dissipation of energy and many efforts are devoted to reduce it to a minimum, for example by using hydrodynamic and compressed air lubrication. In many instances friction is exploited for the service of mankind, such as in braking systems and assembling components using rivets or bolt and nuts. The energy dissipation between dry friction surfaces under vibration has been exploited in vibration control of turbine blades in which the preloading force is caused by centrifugal action on the friction dampers (Sanliturk et al. 2001).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 (Hess 1998). Railway lines are laid on sleepers which in turn rest on a foundation of ballast consisting of crushed hard rocks. At high speeds in excess of 400 km/hours it has been found that dynamic vibrations can set the ballast in motion and some of the rocks can momentarily be separated from the mass of the ballast, they would offer meek resistance to the dynamic load resulting in fast sinking of the railway lines which can lead to derailing (Ricci 2005). These failures can be attributed to vibration induced loss of contact of friction surfaces. Loosening is supposed to take place when the friction forces that exist between surfaces are eliminated in the course of interaction between friction and vibration, resulting in loss of friction leading to relative movement between them. 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. The first study on threaded fastener loosening can be attributed to Goodier and Sweeney (Goodier 1945). One of the most recent experiments on thread fastener loosening were carried out by Hess and associates (Hess 1996, 1997) on a simple nut and bolt assembly and found that for a single bolt assembly, given a moderate pre-load by a spring, that vibration causes both loosening and tightening and that system parameters can be tuned to cause either action or neither action to occur: no change of assembly status for amplitude of vibration below certain level for all frequencies studied (50-1000 Hz), loosening tendency is strong at low frequencies but as frequency increases, the amplitude of vibration to induce loosening is decreased, in fact for large amplitudes, tightening can take place.

A number of analytical models employing rigid bodies have been proposed. Daadbin and Chow, 1992, treated the thread surface of the nut as a spring and dashpot, initially in contact with a rigid incline surface representing the bolt. The spring is initially compressed to represent the pre-load. When an impact force is applied, the spring reaction will force the mass upwards. If the mass is displaced more than the spring's initial compression due to pre-load, the system will be separated from the inclined plane. When the system returns to the surface of the inclined plane, it will fall on the spring and dashpot. An earlier and more complicated model had been studied by Vinogradov and Huang in 1989 with the nut replaced by a discrete five-mass system which are inter-connected by springs and dashpots with Coulomb dry friction model used for the friction between two mated surfaces. A more recent model has been proposed by Hess in which it is assumed that the mated surface are in intimate contact and can be developed into an incline plane representing the bolt and a block representing the nut. These components are under preloading and are treated as rigid bodies, with interfacing modelled by springs and dashpots, dry friction contact and under compressive preloading force. The analytical results produced by the model correlate well with experimental results (Hess 1996, 1997). Finite element method (FEM) which treats the system as deformable bodies has also been used to investigate the threaded fastener loosening (Holland 2002, Pai 2002)).

The research over the last sixty years have brought about understanding the vibration induced thread loosening, albeit conclusive agreement among researchers has yet to be reached. The main reason is that such a simple problem involves many parameters, most of them are very difficult to control (Ramsey 1995).). In order to focus on a number of fundamental parameters, a simple two dimensional model of the system is proposed in this paper.

2 Two dimensional model of frictional surfaces in contact

First it must be said that the instability of railway ballast and thread loosening involves three dimensional deformable systems held together by gravity, friction force and preload. Crushed rocks in a ballast system are polyhedral surfaces of various sizes and orientations coming into contact in a random fashion during the pouring, tampering and loading processes. Threaded surfaces of bolts and nuts have a more regular defined geometry, however due to inaccuracy in manufacturing there exists variation in surface finish and dimensions resulting in changing degree of interference and preloading between two mated threads. It is also well known that only a few threads are actually taking the load and responsible for the deformation. In order to focus on a number of fundamental parameters, in this paper, a simple two dimensional model of the system is proposed. This model takes into account the deformability of the system and fundamental parameters of the interaction between vibration and friction. By assuming the regular pattern of threaded surfaces, by assuming the thread width is small to the diameter of the thread and ignoring small variation due to manufacturing, a two-dimensional model of the frictional contact surfaces can be used, in which the threaded surface of the bolt is developed into an incline plane and that of the nut is modeled as a block in contact with the incline and under gravity, frictional force and preload force. This model with both bodies considered as rigid bodies has been successfully used in textbooks on design and theory of machines (Green 1962, Shigley 2003) for static analysis. In this paper both bodies are treated as deformable bodies and effects of dynamic loading of harmonic vibration on the system are investigated by experimental studies and finite element simulation.

3. Experimental studies of a block incline model

The harmonic excitation on the block and incline model was effected by a shaker. The incline consisted of three components bolted together: an incline plate, base plate, side plate. The block has a thin layer of steel sheeting to simulate a steel surface. The base is screwed onto the shaker. The block and the incline have a combined mass of 6 kilograms. The total mass was limited by the maximum force tolerated by the shaker imparting the vibration. Preloading was effected by using up to 11 small magnets inserted into holes countersunk in 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. A sliver of steel sheet or shim of 0.3 mm thick was placed over the base of the block to provide a smooth surface. The components of the experimental set up are shown in Figure 1.

Figure 1: Experimental set up for the block-incline model

Acceleration signals from the base and the incline were conditioned by charge amplifiers and fed into a Data-Physics data acquisition card, and then analyzed using HPVEE software. The sampling rates for all of the experiments were taken at 1000Hz for a duration of five seconds. The state of the excitation force measured by Gs and its frequency were set and monitored for each test. Maximum acceleration that could be achieved was 30 Gs. Preload was effected by magnets inserted into the base of the block. Different combinations of preload were varied by changing the pattern of the magnets in the base of the block, ensuring at the same time uniform and symmetrical distribution of magnetic force. Three levels of preload were used: Minimum, Medium and Maximum Preload corresponding to 6, 13 and 23 Newtons repectively.

It was observed that when the block-incline is subjected to harmonic vibration, for the same level of preload, depending on the combination of harmonic excitation amplitude measured in G and frequency (Hz), one of three scenarios could happen: the block is stationary with respect to the incline (termed as no effect) corresponding to no relative twist of threaded surfaces, the block moves up the incline (movement up) for thread tightening, and the block moves down the incline (movement down) for thread loosening. The results for three levels of preloading are shown in Figures 2a-c.

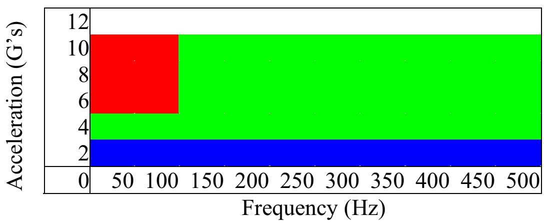

Figure 2a: Minimum Preload

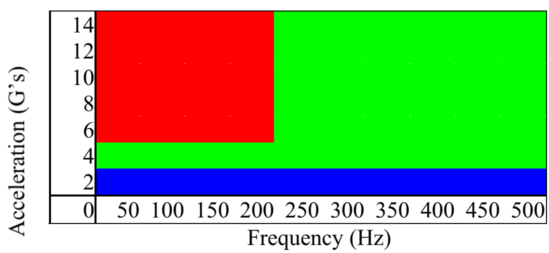

Figure 2b: Medium Preload

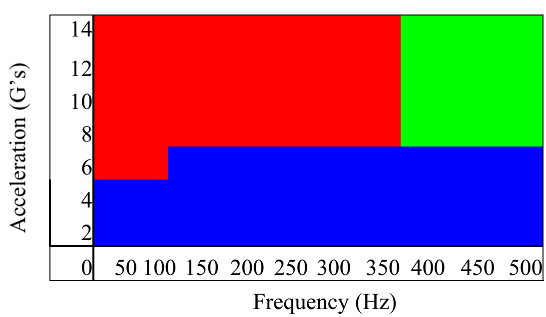

Figure 2c: Maximum Preload

Movement Up Movement Down No Effect

These states form clear regions on the plane of acceleration amplitude-frequency. The representation of each region is as follows: dark-grey for movement of the block up the incline surface, grey for movement down, and dark for no effect. In polychromatic plot the colours are red, blue and green respectively. With the level of preload increases, the region of tightening and, to a lesser extent, the region of no effect, expand at the expense of the loosening region.

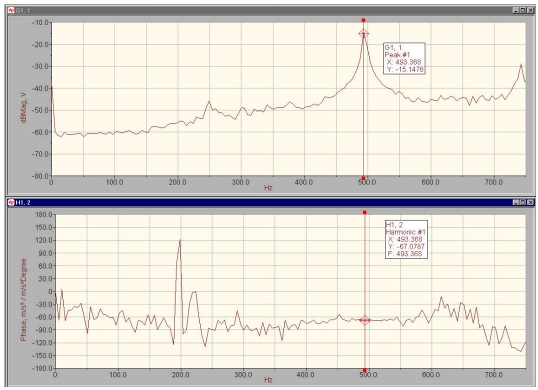

Figure 3: Frequency distribution of magnitude and phase of accelerations in loosening at 500 Hz

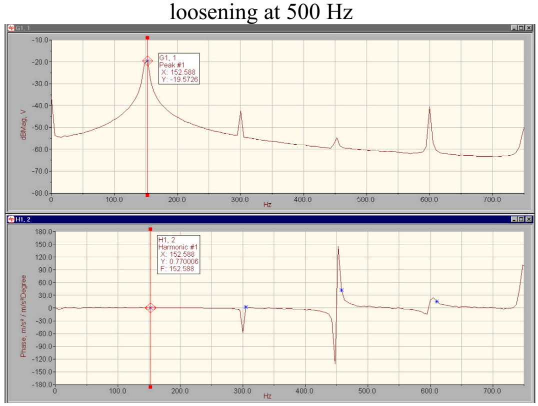

Figure 4: Frequency distribution of magnitude and phase of acceleration in tightening at 150 Hz

The time signals of accelerations of the block and incline were recorded and processed to yield the relative amplitude and phase difference plot in frequency domain and are shown in Figure 3 and 4, the former encapsulates cases of loosening at 500 Hz and the latter tightening at 150 Hz. It can be seen that during loosening, a changing phase difference is found between the acceleration of the block and the incline, and tightening on the other hand happens with hardly any phase difference between the two signals. Evidence of clattering at various frequencies is very clear in Figure 3 with overall loosening, while in Figure 4, the tightening effect ensures intimate contact, only well defined super-harmonics (frequencies of higher or multiples of excitation frequency) were observed.