Model Reduction for Impact-Contact Dynamics of Multibody Dynamical Systems

**Project Objectives**

Develop a model order reduction (MOR) method for dynamic simulation of multibody systems with multi-point and frictional contacts. Using the new method, contact dynamics simulation speed can be increased by *one to several orders* and simulation procedure becomes more robust.

**Motivation**

Model order reduction technology for simulation of structure dynamics with small deflections has been well developed and widely used in industry for the benefits of reducing computational burden and improving numerical performance. However, the technology cannot be readily applied to a dynamic system involving impact-contact motions because the contact dynamics is highly nonlinear plus the contact forces, as input to the system, are not part of the structure model. As a result, contact dynamics simulations of multibody systems are very time consuming and also numerically troublesome. This makes simulation-based engineering verification or analysis of space systems very inefficient.

**Approach**

In the method the nonlinear contact force model and the multibody dynamics model are linearized by introducing a set of perturbation variables within selected time intervals. This allows the implicit contribution of the contact stiffness to the system dynamics to be identified and then added to the structure stiffness of the multibody system. Following this, the well-developed modal analysis and reduction techniques can be applied to reduce the order of the overall dynamics model. As a result of the process, the “high frequency” components of the contact dynamics model appearing on the right-hand side of the dynamics equations will also be reduced and the resulting dynamics model becomes much easier to integrate numerically. The technique under study can lead to a significant boost in the computational efficiency and numerical robustness of otherwise difficult contact dynamics simulations of general dynamic systems performing complex contact activities.

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Systematic Identification of Impact-Contact Dynamics Model Parameters

Objectives
Develop and experimentally validate a systematic method for simultaneously identifying all the stiffness, friction, and damping parameters of impact-contact dynamics models of complicated contact hardware (see examples below). The largest advantage of this method is to allow engineers to tune their contact dynamics simulation models directly from lab or field tests of the real contact hardware of interest as opposed to using specially-cut specimen.

Motivation
The accuracy of a dynamic simulation depends not only on the mathematical model (i.e., formulation, algorithms, and computer code) but also on the values of model parameters. A high-fidelity models like the ones shown in the pictures can have many parameters. Efficient identification of these parameters is very difficult. It would be ideal if such identification can be done with an already assembled hardware or directly using a scheduled routine test of the contact hardware as opposed to using specially made test specimens on specialized testing facilities. This research solves this problem.

Approach
The methodology under study solves the multiple-contact problem by avoiding the direct measurement of each of the local contact locations and contact forces. Contact locations are estimated from a known geometry model of the contacting bodies and their global poses (positions and orientations). The measurement of the pose of a rigid body is much less difficult than the measurement of all the unperceivable contact locations. Such an approach allows the estimation of the contact parameters directly from the testing of engineering models. The overall procedure of the proposed method is conceptually illustrated in the following figure. The key of the method is to make use of the geometric model of contacting bodies to estimate the locations and surface deflections of all the local contact points. In other words, the method assumes that the geometry of the contacting bodies is known in advance. This is not an impractical assumption in practice because geometry models of contact interfaces must be available from design data. The novelty of such an approach is that it applies particularly to complex contact geometries where contact happens simultaneously at multiple areas in a time-variant fashion, while other known estimation algorithms from the literature deal with only single-area contact problems.

Selected Publications
Validation of a New Friction Model

Introduction

- Friction behaviour usually consists of two regimes: the sticking regime (static friction) and the sliding regime (kinetic friction).
- The most commonly used friction force model in engineering is the Coulomb friction force model. The Coulomb model explains some friction phenomena, however, it does not describe friction near zero velocity well.
- Many research efforts have been made in the past few decades to develop friction models capable of overcoming the Coulomb models’ drawbacks.
- These models, however, have to be extensively modified when they are applied to general three-dimensional contact situations. Most models become discontinuous when applied to three dimensional situations or are not standalone models making them difficult to implement.
- A new friction model is presented that is an extension of the popular one-dimensional bristle friction model to two dimensional space. With this extension, the new model is able to model three-dimensional contact very well because it can accurately model friction behavior, it is continuous and it is a standalone model.
- The equation for the new model is shown in equations 1 through 3 where $v$ is the contact relative velocity, $k$ is the bristle stiffness, $C$ is the bristle damping coefficient, $f_{b}$ is the bristle deflection, $f_{c}$ is the bristle velocity, $f_{r}$ is the contact force, $a_{u}$ is the static friction coefficient, $a_{k}$ is the kinetic friction coefficient, $v_{b}$ is the bristle velocity and $v_{d}$ is the maximum bristle deflection.

\[ f_{b} = -k \cdot C \cdot v_{b} \]  
\[ f_{c} = -a_{k} \cdot f_{b} \]  
\[ f_{r} = -a_{u} \cdot f_{c} \]

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Friction Subroutine in MD Adams

Contact is very difficult to simulate. This is because equations must be derived to determine when contact happens. Depending on the shape of the geometry, this can be very difficult. Due to the high cost of hard contact, a multi contact point jarring example was used consisting of a peg falling into a hole.

The subroutine was specifically developed to be implemented into any contact simulation. In order to do this, it must be compatible with all of Adams' different integrators. For example, some integrators change the time step (variable time-step integrators) if the result of a time step does not converge to a solution within a specified error. If this happens, then the time step is changed and the previous data is not used. This is a problem, because the new model has integration which needs data from previous time steps. The subroutine was changed to examine the input and output data and save data for the next time step only when a result has successfully converged. Once completed, the FORTRAN subroutine was verified by doing multiple simulations.

Experimental Validation

Experiment 1

In the experiment a block first rests between two parallel rails fixed horizontally to the top of an adjustable inclined plate as shown in Figure 2, where the x coordinate is normal to the inclined plate. The block is given a push along the rails (the y direction). As a result, the block will slide out of the rails and continue sliding on the inclined plate both forward (due to the initial velocity) and downward (due to the gravity force) until it stops after a little while (due to the friction). An infrared-based high-accuracy 3D motion tracking system called OPTOTRAK is used to capture the motion trajectory of the block. An initial velocity for the block was measured in the experiment as it left the constraint rails, and then a simulation having the same initial velocity was performed. The simulation and experimental data are plotted in Figure 3.

Experiment 2

The experiment consists of a spring-constrained block on a rotating table (Figure 4). While the table is rotating, the block will have momentary sliding and sticking behavior. The experiment and simulation results are shown in Figure 5. The experiment’s relative velocity peaks vary through time while the simulation’s has less variation because there were disturbances in the experiment. These disturbances are very difficult to be identified and modeled. For example, small irregular motion is transferred to the block from the rotating table. Also, the static and kinetic friction coefficients are not perfectly even across the surface of the table. All these disturbances cause the amplitude and period of the experimental result to be slightly different from one stick-slip cycle to another. Having said all this, the comparison between the experiment and simulation, is still considered very good match.

Multiple Contact Simulation

The last step in fully verifying the model is to see how well it works with different contact scenarios. A multi contact point jarring example was used consisting of a peg falling into a hole. Figure 6 shows the motion of the peg after (a) is in its resting condition, (b) the peg makes a single contact with the hole and slides into it and (c) the peg has two contact points and jams inside the hole.

The simulation was solved using Matlab. The contact equations for every possible orientation of the peg and hole in jamming were derived. It was found that there were two different orientations (thus two different equations needed to be derived). The contact point and penetration depth were found for each orientation using geometry similar to that shown in Figure 7. The simulation was run and the results are shown in Figure 8. The friction and contact force decay while oscillating once the peg has jammed because they are both modeled using springs and dampers.

Conclusions

- A new 3D-dimensional bristle friction force model was developed. The model is particularly suitable for the modeling and simulation of 3D contact dynamics of multibody systems.
- The new friction force model has been experimentally validated. Two different experiments were conducted and compared to the simulation cases. The first simulation matched the experiment very well. The second simulation did not match the experimental case as well, however, this was because of disturbances to the motion of the block in the experiment that could not be accurately modeled. When considering this, the second simulation results are also acceptable.

- A FORTRAN subroutine was developed to be used with Adams to simulate any contact simulation. The subroutine was specifically developed to be able to work with fixed step of variable step integrators.
- A multiple contact jarring simulation was presented and showed the friction models ability to simulate complex contact systems.

Publications


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