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Applied and Computational Mechanics 1 (2007) 351 - 356

Applied and
Computational
Mechanics

Criteria of benchmark selection for efficient flexible multibody system formalisms

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Received 20 September 2007; received in revised form 3 October 2007

Abstract

The paper deals with the selection process of benchmarks for testing and comparing efficient flexible multibody formalisms. The existing benchmarks are briefly summarized. The purposes for benchmark selection are investigated. The result of this analysis is the formulation of the criteria of benchmark selection for flexible multibody formalisms. Based on them the initial set of suitable benchmarks is described. Besides that the evaluation measures are revised and extended.

Keywords: benchmark, flexible multibody system, efficient multibody formalism

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1. Introduction

Dynamic simulation of multibody systems (MBS), especially more of flexible multibody systems (FMBS) is very important not only for solving dynamics of traditional mechanical systems, but even more for investigation of mechatronic systems where MBS is usually the kernel of the model. Precise, reliable and efficient computer simulation of FMBS is the basis for their optimized design and for the design of suitable control system.

Standardized problems, so called benchmarks, of MBS and FMBS are of great interests for the development of new advanced formulation and simulation techniques. The new methods must be compared with the previous ones regarding many features. The compared property of different formulations and implementations is usually the computational efficiency resulting into the ultimate CPU time necessary for the simulation of particular benchmark problem. The other important properties to be compared are discussed later.

A certain set of benchmarks for MBS and some FMBS simulation has been proposed and defined in the past. However, the new developments of flexible multibody system formalisms and the new developments of multibody formalisms for usage on parallel processors require to develop suitable set of benchmarks and suitable methods of their comparisons.

In this paper it is described the way of selection of benchmarks for testing and comparing efficient flexible multibody formalisms with respect to their parallelization. The paper is organized as follows. The section 2 deals with the overview of existing MBS benchmarks. The description of the suitable comparison criteria that are used for the benchmark selection is provided in section 3. The proposed list of suitable benchmarks is the content of section 4. Finally the conclusion is in section 5.

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2. Overview of existing benchmarks

The benchmarking of different multibody formulations has originated in robotics. The used benchmark was the robotic structure of Stanford arm, but then the comparison was done on the open loop kinematical chain consisting of *n* consecutive bodies connected by revolute kinematical joints of general orientation. The computational complexity of such chains gave rise of the so-called *O(n)* formalisms. An overview of historical improvement of computational efficiency is in [11].

However, the first comprehensive comparison of available general purpose MBS formalisms was done in [10] where also two benchmarks of rigid MBS have been specified. They were a 6 DOFs serial robotic manipulator and a 7 link Andrew's mechanism. But these benchmarks were evaluated just qualitatively. The next important effort was carried out by IAVSD (International Association of Vehicle System Dynamics). Two benchmarks for road vehicles and two benchmarks for rail vehicles were defined [7] and the results were qualitatively evaluated [8] whether a certain formalism/computer code can solve the benchmark. The road benchmarks consist of five-link wheel suspension mechanism and 4x4 Bombardier Iltis vehicle. The rail benchmarks were more devoted to the phenomena of rail contact than to general MBS problems.

Then many other authors have proposed and used different benchmarks mainly for testing the capability of new simulation methods to cope with certain phenomena in MBS dynamics. An overview of these efforts has been summarized in [4]. The list of these phenomena is important for our further consideration of proper benchmark selection. The majority of them belongs to the area of rigid MBS. These phenomena of rigid MBS were the singularity during the MBS motion, undergoing singular positions, higher number of constraints, very small time scale, stiff dynamic system.

In the area of flexible MBS the list of investigated benchmarks is significantly smaller. They consist of single flexible robotic arm [3, 9] or hinged beam [2], planar and spatial slider crank mechanism [5, 6] and four bar mechanisms [1]. Beside that many authors have studied the rigid-flexible mechanisms where for example the middle link of four bar or slider crank mechanisms is flexible and other links are rigid. The fundamental difference between rigid and flexible MBS benchmarks is that the comparison and validation of results is for flexible MBS much more difficult. If for rigid MBS it is theoretically possible to compare and validate the equations of motion symbolically with clear confidence of equation correctness. It is based on the fact that rigid MBS have finite number of DOFs and the equations of motion are exactly formulated in the coordinates of these DOFs. This is completely different for flexible MBS which have infinite number of DOFs and the equations of motion are always assembled as approximative equations of motion. Very different approximations can lead to very close results. On the other hand for flexible MBS it is highly advisable to conduct real experiments and to compare the numerical results not only among them but also or even primarily with the experimental measurements. This fact decreases the number of available suitable benchmarks for flexible MBS.

Finally recent efforts for establishing a suitable set of benchmarks are described in [4]. The previous benchmarks are summarized, the problems of benchmarks described and a revised set of benchmarks proposed and developed. However, the developed set of benchmarks is oriented towards rigid MBS and the main performance index is the computational complexity in relationship with accuracy of simulation results. This is important but it is not enough especially for flexible MBS. The simulation of flexible MBS meet with the problems whether certain dynamical phenomena are at least qualitatively correctly modeled and simulated. Besides that the proposed set of benchmarks does not include flexible MBS at all.

3. Suitable criteria for benchmark selection and evaluation

The suitable set of benchmarks must fulfill certain criteria in order to comply with the expected purpose. The purpose of the set of benchmarks that are to be assembled is to develop and test different formalisms for flexible MBS and the simulation of flexible MBS on parallel processors with high number of units.

Therefore the criteria for benchmark selection are following:

- Dynamic phenomena occurring during the simulation of rigid MBS: kinematical loops leading to constraints, singular MBS through whole motion, MBS undergoing through singular positions, very small time scale, stiff systems.
- Dynamic phenomena occurring during the simulation of flexible MBS: small/large deformations, small/large rotations, stiffening, prismatic joint between flexible bodies.
- General computational complexity: long kinematical chains, increased number of kinematical loops - constraints, difficult time integration – stiff, very small time scale.
- Computational complexity with respect to the solution on parallel processors: different topologies of MBS – parallel loosely/tightly connected MBS parts.

The other problem of benchmarking is to develop and use suitable evaluation criteria. In [4] the computational complexity of MBS formalism is proposed to be measured in the relationship with the achieved accuracy of the benchmark solution. The accuracy of the benchmark solution is evaluated by the relative error between the achieved and referenced outputs of the investigated MBS benchmark. It is important that the outputs can be not only positions, but also velocities, accelerations, forces or even further specified quantities. For flexible MBS especially important sensitive quantity is the sequence of eigenfrequencies maybe together with eigenmodes. This measure of accuracy e_{total} is computed by the formulas

$$\begin{aligned} e_j(t_i) &= \frac{\left| y_j(t_i) - y_j^{ref}(t_i) \right|}{\max\{\left| y_j^{ref}(t_i) \right|, y_j^{threshold}\}} \\ e_{total} &= \sqrt{\frac{1}{m}\sum_{i=1}^{m}\frac{1}{n}\sum_{j=1}^{n}(e_j(t_i))^2} \end{aligned} \tag{1}$$

where $y_j(t_i)$ is the obtained solution for the variable j at the time t_i, $y_j^{ref}(t_i)$ is the reference solution for the variable j at the time t_i, $y_j^{threshold}(t_i)$ is a threshold introduced in order to overcome singularities if the variable goes through zero value. The drawback of this measure is that its values become large just by small phase shift at oscillatory motions. The solutions in such cases would not be evaluated as large difference if the same behaviour is obtained.

Therefore other measures are necessary to evaluate the difference between solutions in cases of phase (time delay) differences between both results. The measure e_{cor} that would be insensitive to these differences is the maximum correlation

$$e_{cor} = \max_{\tau} Cor(y_j(t+\tau), y_j^{ref}(t)) \tag{2}$$

Between the reference solution and the obtained solution shifted by some time shift τ that corresponds to average phase shift or time delay discussed above.

Another measure is derived from the comparison of the envelopes of the reference and obtained solutions. This is helpful again in the case of highly oscillatory solutions. The computed envelopes are compared using the formula (1) or (2). The goal is to develop a measure for similarity of two solutions that are different but man would judge them as similar.

The other not very precise measure is the evaluation of computational complexity by the total CPU time necessary for the solution of the investigated benchmark on the given computer. It is the ultimate objective quantity, but two problems are associated with that. First, this makes difficult to compare two different hardwares and this is necessary in the case of parallel processors that are always compared with the solution on a single processor. Second, this brings the influence of selected integration method although some choice is dependent on formulation of equations of motion (e.g. ODE or DAE).

Therefore further measures of computational complexity are necessary and helpful. The traditional measure was the number of operations (addition/subtraction, multiplication/division, trigonometric function) necessary for the computation of accelerations that are then numerically integrated. The problem of this measure is that it neglects the different effort necessary by the integration procedure for the integration of minimum coordinates and of redundant coordinates. The other neglected effort is the possible correction of coordinates after the integration step (by projection, Newton-Raphson method) in order to satisfy the constraints.

This measure must be improved in such way that the number of operations is extended by the effort of integration procedure and of correction procedure in one time step. This can be done either by the direct computation of the number of operations necessary for the time integration and correction procedure by really used procedures or by the computation of some equivalent number of operations, e.g. computing the number of operations of typical integration and correction procedures, certainly in the number of integrated coordinates. It is the same as the consideration of Gauss elimination for the system of linear algebraic equations accounted for in the traditional computational measures as in [11].

4. Proposed set of benchmarks for efficient flexible multibody system formalisms

Based on the criteria for benchmark selection the initial suitable set of benchmarks for flexible MBS can be proposed. It is useful to combine the traditional benchmarks for rigid MBS with the new ones for flexible MBS.

The computational complexity of rigid MBS has been investigated on the N-ary pendulum (planar, spatial) that is a N-ary kinematical chain with revolute joints (Fig. 1). The dependence on the increasing length N of the chain is important. The other parametric set of benchmarks can be based on the structure with 1 DOF and with the increasing number of kinematical loops where the parameter of the structure is the length of the kinematical loop with the minimum length. Example of such structure is on Fig. 2. The length of the minimum loop (kinematical loop with the minimum length) as the parameter is 5. The structure has 0 DOFs, but removing one body from the frame creates a mechanism with 1 DOF and the same property. These parametric structures should be investigated as rigid MBS as well as flexible MBS.

The other set of benchmarks is the set of elementary planar and spatial flexible mechanisms such as slider crank, four bar. The real experiments have been done with these flexible mechanisms and they would be the basis for investigation of correct simulation of flexibility of MBS. These mechanisms can be considered with all flexible bodies and just with one middle flexible body. Solution results can be found in the literature for both cases.

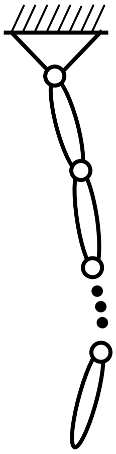

Fig. 1. N-ary chain with revolute joints.

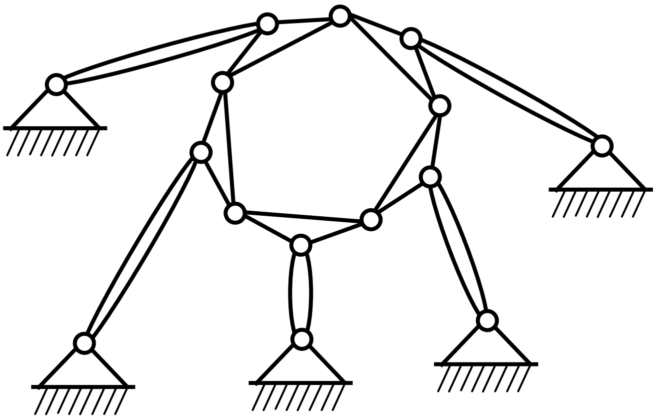

Fig. 2. Structure with increasing length of minimum loop.

Robotics offer several sources of benchmarks. The serial kinematical structures suitable for benchmarks include the serial robotic arms with revolute joints as already on Fig. 1. The other important serial kinematical structures for benchmarks of flexible MBS are those with prismatic joints. With the change of position of prismatic joints the eigenfrequencies change rapidly. There are two possibilities – just prismatic joints or alternated with revolute ones – see Fig. 3. The robotic parallel kinematical structures both rigid and flexible are the other set of benchmarks. This includes the hexapod, hexaslide, octapod, octaslide and other similar structures (e.g. [12]).

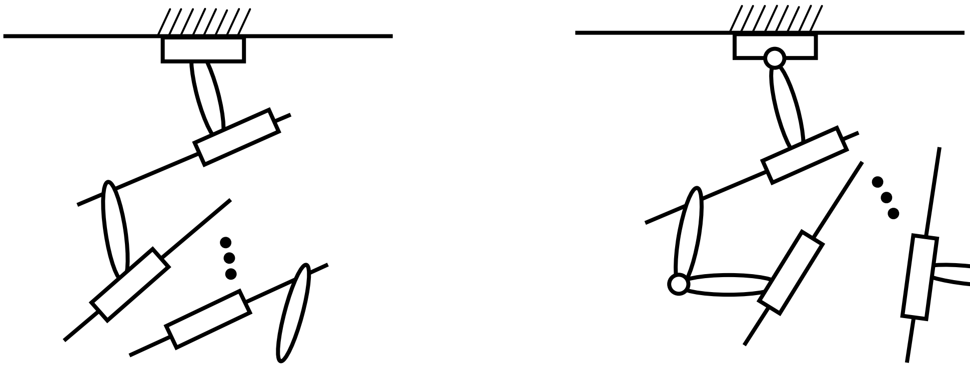

Fig. 3. Two variants of serial robotic arm with prismatic joints.

The important set of benchmarks is the set of examples of phenomena of geometric stiffening in flexible MBS. The classical example is helicopter blade.

The other set of benchmarks includes the examples of MBS with singularities. It can include Bricard’s [4] or Turbula [11] mechanisms for permanent singularity and the N-four bar mechanism [4] for undergoing singularities during the motion. The examples of deployable structures belong to this class of benchmarks.

The final group of benchmarks consists of MBS that are difficult to be integrated as Andrew’s mechanism [10] or flyball governor [4].

5. Conclusion

In the paper the current state-of-the-art of benchmarks for MBS is summarized. The criteria for benchmark selection for flexible MBS and parallelized MBS formalisms are proposed. The existing evaluation measures of MBS benchmarks are revised and extended towards flexible MBS. Finally the initial set of benchmarks for development of formalisms for flexible MBS and parallel computers is described.

Acknowledgements

The authors appreciate kind support of the project GAČR 101/07/J075.

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