

# CONTACT PROCESSING IN THE SIMULATION OF THE MULTI-BODY SYSTEMS

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## Abstract

Contact processing, including collision detection and contact response, is one of the most difficult, but most important areas in the simulation of the multi-body systems. However, the most widespread multi-body simulators, like Matlab/SimMechanics, don't support the contact processing. Other multi-body simulators, like Vortex or ODE, support the contact processing, but are more limited in the rest of the functionality. This paper presents the overview of the most popular techniques in the contact processing by simulation of the multi-body systems and shows the implementation of the chosen contact processing technique into Matlab/Simulink. The collision detection has been implemented using existing software tool Solid. The contact response for both contact phenomena - collision forces and friction forces – has been developed for the force-based approach. The functionality of the developed contact processing has been performed by the contact tasks of an anthropomorphic manipulator and a six-legged robot. Both kinds of robots represent the structures with serial and parallel kinematics respectively. They are typical multi-body systems for investigation of the single and multiple contacts as well as the stiff connected with environment and the free moved in environment respectively. The functionality of the developed contact processing has been compared with identical contact tasks in Vortex.

**Keywords: contact processing, collision detection, contact response, contact forces and torques.**

## Presenting Author's biography

Vadym Rusin received the Dipl.-Ing. and the M.Sc. degrees from Technical State University of Donetsk (Ukraine) in 1998 and 1999, respectively, all in electrical drive and automation. Since 2000 PhD student at the University in Magdeburg (Germany) and research engineer at the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg (Germany). Working fields: industrial automation, mobile and service robots, intelligent drives control, simulation of the mechatronical systems. About 20 publications.



## 1 Introduction

In the mechanical systems certain machine elements usually interact with each other. When a mathematical model of such system is designed, the interactions between the parts can be divided in two following categories:

- Mechanical joints are used for defining permanent constraints of a motion.
- Mechanical contacts are almost instantaneous, typically short-time interactions caused by non-penetration contact forces arising between the bodies in the model.

The forces occur when the surfaces of bodies touch each other. Two major phenomena occur in the mechanical contacts: collision contacts (causing collision response forces) and friction contacts (causing static or dynamic friction forces).

Contact processing is a difficult task [1, 5, 6]. The bodies can move in a complicated way, and they can have complex geometries. In the case of contacting bodies, the penetration of them must be prevented. There is a trade off between efficiency and accuracy. Accurate methods for computing contact forces are based on finite element methods. Such methods are based on subdivision of bodies into very small fragments. The surfaces of two colliding bodies are to be covered by a mesh and the relevant forces in the contact are to be computed for each point on the mesh. The resulting forces can be defined by integration of all forces acting on the contact surface. These methods are implemented in software packages for FEM-analysis (ANSYS, Nastran etc) or in multi-body simulation (MSC Adams etc). Experiments [2] show that these methods are accurate, but require tremendous computing resources and therefore are very slow. However, many simulation applications do not require extreme accuracy and additional assumptions are taken into account providing high simulation speed, but decreasing the accuracy. As a matter of fact, different assumptions lead to different computation methods but with the same (or nearly the same) computation results. In such cases, it's not important for the application what assumptions and methods were used.

The goal of this paper is to present the ways of adding contact processing (chapter 2) to existing mechanical multi-body simulator Matlab/SimMechanics and to compare them with contact processing in Vortex, which is characterized by internal optimization loop with considering of energy and impulse conservation law. The results are presented though the example of contact tasks for an anthropomorphic manipulator and for a six-legged robot (chapter 3).

## 2 Contact Processing

Implementation of the contact processing is based on the following steps.

- Mechanical models, which describe physical bodies, should be extended to describe contacting physical bodies.
- There should be a routine that can detect collisions and can return detailed information regarding contact parameters, such as contact points and their velocities.
- A special routine should calculate the contact response from contact parameters.
- Each of these components should have an interface that allows replacing its implementation without doing major redesign of the other components.

Fig. 1 presents four basic components of contact processing, which are derived from the discussion above and will be described more detailed later.

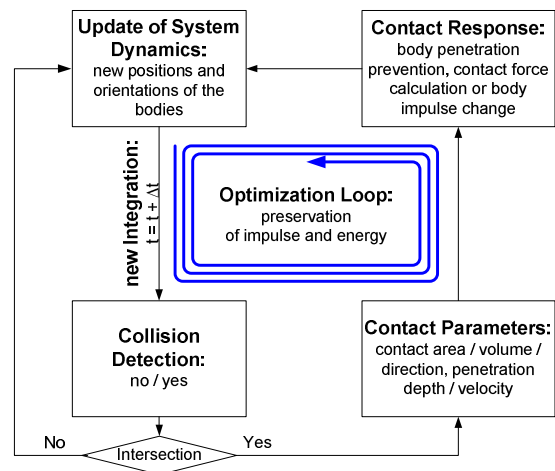


Fig. 1 General scheme of contact processing in the mechanical multi-body simulation.

### 2.1 Collision Detection

The collision detection between bodies, which are indirectly described, for example using sets of points in the space, means that the contact points or trajectories between two bodies are to be defined.

In the first part (*collision culling*), the pairs of non-colliding objects should be excluded. These can be performed using the methods of space division like Quadtree/Octree, BSP-Tree, Sweep-and-Prune. The whole space should be divided and the potentially non-colliding objects should be excluded.

In the second part (*broad collision detection*), the possibility of two objects collision by means of so-called Bounding Volumes like AABB, sphere, OBB, k-DOP should be defined. These covers simplify the complex geometry objects and make the collision detection simpler and faster.

The third part (*exact collision detection*) defines the collision between the contacting objects. Spatial, hierarchical data structure, as AABB-tree, OBB-tree, sphere-tree or k-DOP-tree should be used for faster collision definition.

## 2.2 Contact Parameters

The intersection test follows the third part of collision detection and finds the geometrical contact parameters, as contact plane, contact volume, contact normal and penetration, with the aim of the following methods: intersection point of ray and sphere, intersection point of ray and plane, intersection point of ray and triangle, intersection line of two planes, intersection line (point) of two triangles. The presented on the market algorithms (Lin-Canny Closest Features Algorithm, I/Q-COLLIDE, V-Clip, OBB-Tree, QuickCD, KDS, GJK, GJK-based EPA) combine “collision detection” and “contact parameters detection” tasks [7,8,9,10,11] and are implemented in the leading software, e.g. SWIFT, SOLID, ODE and others.

## 2.3 Contact Response

The contact response seems to be the most problematic and controversial part of the contact processing, since many computation approaches exist, which require different input information and may produce quite different numerical results. The following two methods are commonly used in the contact processing: the impulse-based method and the force-based method. Both assume that the bodies are rigid. The update of system dynamics is closely connected with calculation of contact response and therefore both parts should be explained together.

### A. Impulse-based Approach

The impulse-based approach uses collision impulses between the bodies and changes the velocity vector of the bodies during the contact [3,4]. This method based on an impact law such as Poisson’s hypothesis. It considers the impulse conservation law and operates with the impulses of the colliding bodies before and after the collision as well as with the restitution coefficient of materials.

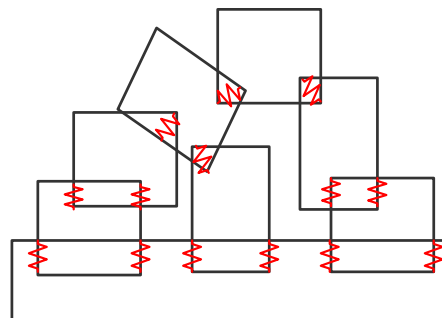
The main advantages of this method are that only a few constants are needed for description of the impact law and that the integrator step size is not influenced by the response calculation because it is performed during an infinitely small time instant. However, since the velocity is not continuous in the impulse-based model, the traditional ODE solvers can’t be used. The continuous integration process in the solver should be stopped at the instant of collision and should be resumed with a new velocity. The impulse-based approach can be easily used in MBS-based models if the collision impact on the other bodies in the system is negligible (i.e. in the system of free-flying bodies). In the other words, this approach can’t be used in the cases of a static objects and structures consisting of several bodies connected by joints. Furthermore such idealized impact laws are only useful for stiff collisions. These properties restrict the applicability of the impulse-based method of the dynamical analysis.

### B. Force-based Approach

An alternative approach of contact processing in multi-body mechanical systems is based on the force and torque model of collision. It is assumed that the contacting bodies penetrate each other and the separation forces are caused by this penetration. These forces try to prevent further penetration and to separate the contacting bodies.

The calculation of contact force magnitude is difficult task and is sometimes not motivated by physics, but rather by numeric analysis. The overall result of collision should match physical laws (i.e. preservation of impulse, and preservation of energy). In addition it should be chosen so smooth that numerical methods used in simulation could handle these functions. The many existing methods for the calculation of the force in the mechanical joints and contacts are divided into two following groups:

- *Force based methods with Lagrange multipliers formulation* models the mechanical constraints (contacts and joints) with the reactive forces, which are presented as Lagrange multipliers  $\lambda$ . The constraint forces perform no work on the environment and the physical meaning of the mechanical contact is lost. The mechanical interaction of the bodies caused by the contact is represented by these reactive forces  $\lambda$ , which should be optimized between the simulation steps in the additional optimization loop (s. Fig. 1) under consideration of the energy or/and impulse preservation laws.
- *Force based methods with penalty formulation* models the mechanical contact with the strong possibly nonlinear spring. The active contact/friction forces (s. Fig. 2) perform work on the environment and the physical background of the mechanical contact is not lost. The mechanical interaction of the bodies caused by the contact is represented by the active forces  $F_{\text{CONTACT}}$  and  $F_{\text{FRICTION}}$ , without any additional optimization between the simulation steps.



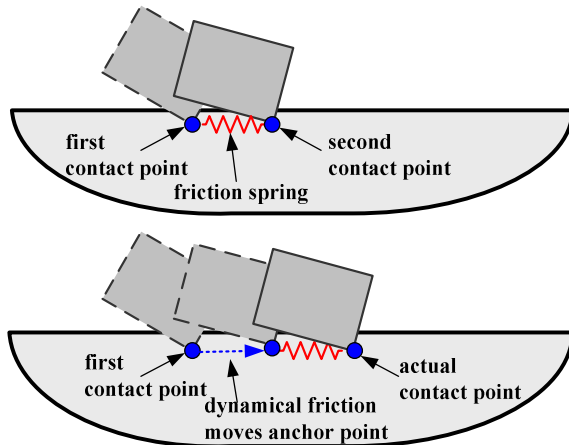


Fig. 2 Force based methods with penalty formulation for contact and friction forces calculation

There are many different equations for determining the contact/friction force magnitudes, which depend on the penetration depth  $p$ , on the penetration velocity  $dp/dt$ , on the frictional penetration  $l$ , and on the Coulomb friction coefficient  $\mu$ . For the purpose of this work the following equation system is chosen for the calculation of the force magnitudes, which is very stable in the wide range of the simulation sample time and corresponds to all above mentioned requirements.

Eq.1 describes the magnitude of the normal force in contact depending on the stiffness  $S_{CONTACT}$  in the contact area, the restitution factor  $\epsilon$  of the materials and the collision velocity  $V_{COLLISION}$  at the first time instant of intersection:

$$F_{CONTACT} = \begin{cases} 0, & p < 0 \\ \left[ 1 + \frac{1 - \epsilon}{\epsilon \cdot v_{COLLISION}} \cdot \dot{p} \right] \cdot S_{CONTACT} \cdot p, & p \geq 0 \end{cases} \quad (1)$$

Eq.2 describes the magnitude of the friction (tangential) force in contact depending on the stiffness  $S_{CONTACT}$  in the contact area (both stiffnesses in the normal and tangential directions are usually identical):

$$F_{FRICTION} = \begin{cases} S_{CONTACT} \cdot l, & S_{CONTACT} \cdot l < \mu \cdot F_{CONTACT} \\ \mu \cdot F_{CONTACT}, & S_{CONTACT} \cdot l \geq \mu \cdot F_{CONTACT} \end{cases} \quad (2)$$

In this case the motion of the anchor point must be considered according to Fig. 2 because it acts on the calculation of the frictional penetration  $l$ .

The main advantages of the force-based approach are the simplicity and the possibility of using it for stiff and soft contacts. This approach works reasonably well if several contact points are also present at the same instant time. The disadvantage of this approach is that the integrator step size should be reduced in the contact phase in order to catch the rapidly changing contact forces and torques. And similar to the impulse-based method there is necessary to choose the

contact parameters (spring, restitution) because the contact force is proportional not only to the penetration depth/velocity but also to the contact area and the contact volume.

## 2.4 Update of System Dynamics

Update of system dynamics take place each integration step depending of the chosen contact response method.

The update of system dynamics by impulse-based approach occurs according to the follow two methods: *Propagation* und *Simultaneous* update.

- *Propagation Update* says that the impulse is calculated and applied only for one contact per time, i.e. the collision events are treated individually.
- *Simultaneous Update* says that the impulses are calculated and applied for all contacts at the same time, i.e. the collision events are treated after an integration step together.

These two models are identical for the contact situations with only one contact point. However they produce different results for the contact situations with several contact points. Fig. 3 shows the results for the simulation of the three identical billiards balls without loss of kinetic energy.

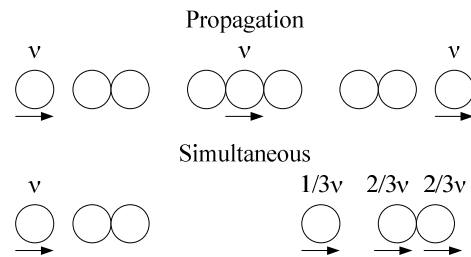


Fig. 3 „Propagation“ vs. „simultaneous“ update of the system dynamics

The update of system dynamics by force-based approach takes place in every integration step depending on the active contact forces. The calculation of the contact forces is often determined by an optimisation algorithm. Besides, its aim is to minimise the function

$$func(F_{CONTACT}) = \sum_{i=1}^N F_{iCONTACT} \quad (3)$$

under the follow contact terms:

$$\mathbf{A} \cdot F_{CONTACT} \geq \mathbf{B} \text{ und } F_{CONTACT} \geq 0 \quad (4)$$

This classical optimisation task from the area of the linear programming is called Linear Complementarity Problem (LCP) and is solved with the help of different algorithms, e.g. Lemke's algorithm or Unique Sinking Orientations. If this optimisation task is to be solved in a multi-body simulator, the appropriate optimisation methods are called several times between two integration steps.

### 3 Simulation of Contact Tasks

The force based contact processing method with penalty formulation presented in chapter 2 has been implemented according to Fig.1 into the multi-domain simulation environments Matlab/Simulink by means of Solid as collision detection software and has been compared with the force based contact processing method with Lagrange multipliers formulation, implemented into multi-body simulation environment Vortex. The anthropomorphic manipulator “Mitsubishi RVE3J” (s. Fig. 4) and the six-legged robot “SLAIR2” (s. Fig. 5) developed at the University of Magdeburg (Germany) and the Fraunhofer Institute for Factory Operation and Automation in Magdeburg have been used as a test subjects.

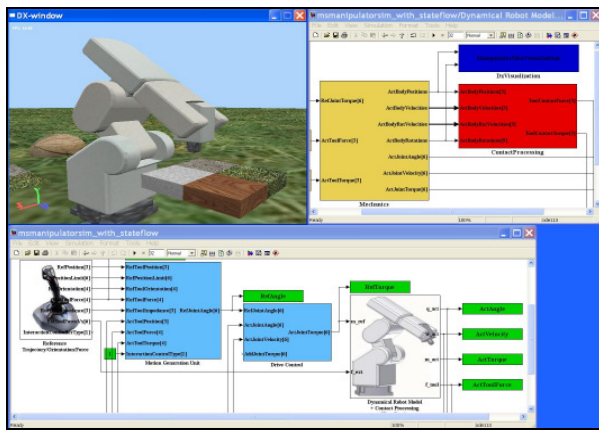


Fig. 4 The anthropomorphic manipulator “Mitsubishi RVE3J” in the multi-domain simulation environment “Matlab/Simulink”

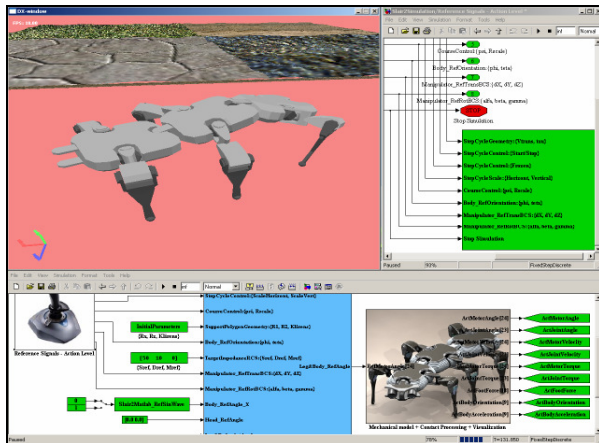
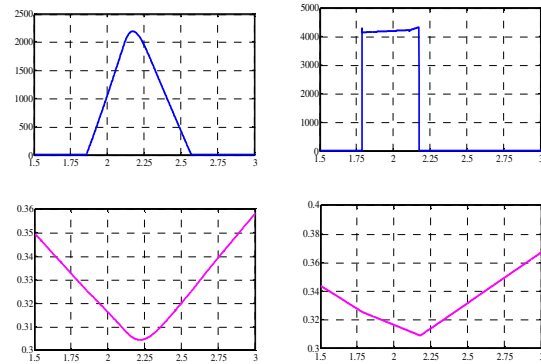


Fig. 5 Modular six-legged robot “Slair2” with articulated body in the multi-domain simulation environment “Matlab/Simulink”

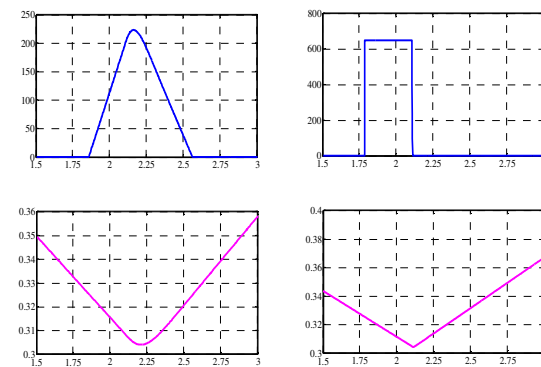
#### 3.1 Anthropomorphic manipulator

Two modes for the anthropomorphic manipulator, normal motion in contact and free motion (normal and tangential) in contact, have been investigated and compared in the mentioned simulation environments.

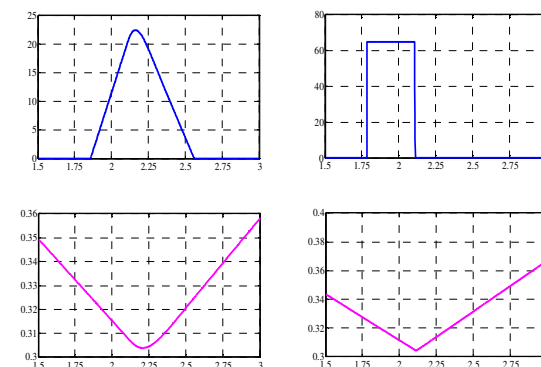
Fig. 6 and Fig. 7 describe the comparison of the forces acting on the manipulator’s tool in both the SimMechanics/Solid and Vortex environments by four different kinds of the environment’s mechanical properties with restitution  $\varepsilon = 0.8$  and stiffness  $S_{CONTACT} = 1e+5$  [N/m],  $1e+4$  [N/m],  $1e+3$  [N/m],  $5e+2$  [N/m] respectively.



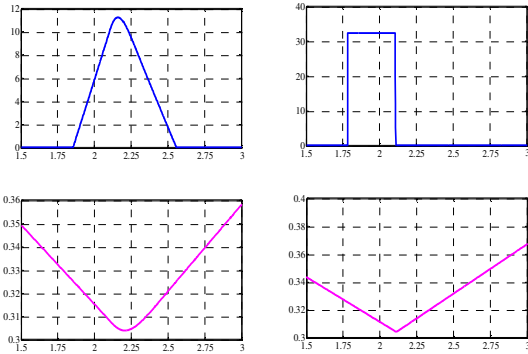
(a)  $S_{ENV} = 100.000$ [N/m]



(b)  $S_{ENV} = 10.000$ [N/m]



(c)  $S_{ENV} = 1.000$ [N/m]



(d)  $S_{ENV} = 500[N/m]$

Fig. 6 Comparison of the forces acting on the robot's tool in (left) SimMechanics/Solid and (right) Vortex by normal contact: blue – normal force, magenta – position in contact.

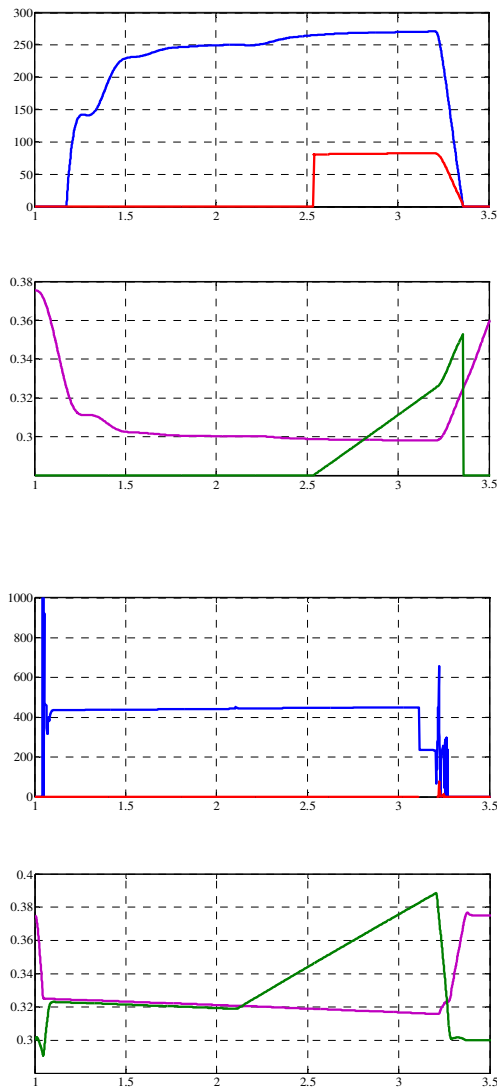


Fig. 7 Comparison of the forces acting on the robot's tool in (left) SimMechanics/Solid and (right) Vortex

by free contact: blue – normal force, red – tangential force, magenta – normal position in contact, green – tangential position in contact.

### 3.2 Six-legged robot

Two modes for the six-legged robot, staying on the ground and moving on the surface, have been investigated and compared in the mentioned simulation environments.

Fig. 8 describes the comparison of the forces acting on the feet of the six-legged robot in both the SimMechanics/Solid and Vortex environments by staying on the ground and doing four steps on the surface. The steps was done with tripod gait.

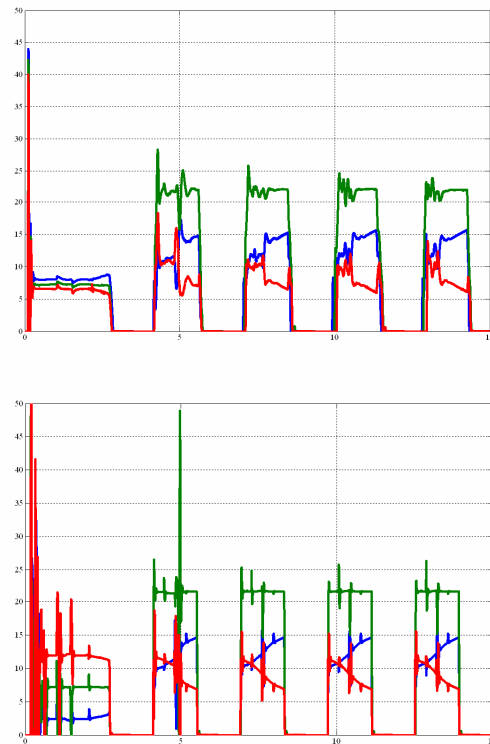


Fig. 8 Comparison of the normal forces under the feet of the six-legged robot "Slair2" staying on the ground and then doing four steps on the surface with tripod gait in (top) SimMechanics/Solid and (down) Vortex: blue – front leg, green – middle leg, red – rear leg.

### 3.3 Conclusion

Research shows that the contact processing in Vortex is robust and close to reality. However in some cases the calculation of the contact forces is not precise, because the solver makes integration using the first-order integration method and the number of the optimization steps is limited to 35 by developers. Besides, in some difficult cases like closed kinematics loop the calculation of the contact forces is even wrong, because the optimization loop redistributes the existing mechanical load between all constraints (joints and contacts).

The developed contact processing environments in Matlab/Simulink are free from aforementioned disadvantages. It can use the integration methods of higher order, and is sufficiently precise by calculation of the contact forces, because Eq.1 and Eq.2 have been laid out under consideration of the energy/impulse preservation law.

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