Dynamics of the Soft Contact Interacting with Rigid Body using Bond-Graph & Finite Element Analysis

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Abstract: **In this paper, research in the dynamics of soft contact interacting with rigid body with advantage of bond-graph and finite element analysis is reviewed. A brief summary of bond graph and finite element analysis is presented. Finite element analysis (F.E.A.) of soft material is done to obtain the stiffness, mass, & damping matrices. For dynamics of soft material, matrices obtained by F.E.A is used in bond-graph as C-field, I-field, & R-field. The model is tested through simulation. Simulation code is developed in MATLAB.**

Key words: Bond-graph, finite element analysis, soft contact, C-field, I-field, R-field.

I. INTRODUCTION

Soft contact interaction plays an important role in many applications. During the soft contact interaction, the contact force is distributed over an area of contact unlike the hard contact, where the contact force is considered to occur at a point. The estimation of contact force and its distribution requires knowledge of contact characteristics, including relationship between forces and contact area and pressure distribution profile at the contact interface. It is therefore quite interesting to analyze the contact mechanics of rigid bodies interacting with soft materials, especially when viewed from the perspective of robotics and control.

The soft material in between the object and robotic fingers affects the kinematics and dynamics of the system during grasping and manipulation. The deformation effect of soft material of robotic fingertips is a useful feature in general robotic application. Moreover, soft material contact mechanics plays an important role in grasping stability as well as safe object handling during manipulation. However, the deformation effect of soft material during the contact tasks is not well understood and hence is drawing a lot of research attention in robotics, especially due to its applications in biomechanics and prosthetics. The development of forces and moments at the contact interface due to the change in the contact area during manipulation also needs analysis.

The conventional approach so far has been to consider soft contact based on point contact. Hertz first studied contact mechanics in 1882, based on contact between two linear elastic materials [1]. Hertz's model can be used to predict the elasticity at each contact as well as the pressure distribution across each contact patch. Later, the study of contact mechanics became a branch in mechanics [1]. Kwi-Ho Park, Byoung-Ho-Kim, and Shinichi Hirai [2] developed a hemisphere-shaped soft fingertip for soft fingers and presented its modeling based on force distribution. Assuming that the materials of soft fingers, e.g. Rubber, Silicon and human tissue are nonlinear elastic, they proposed a relationship between the normal force and area of contact. Nicholas Xydas and Imin Kao proposed a soft-contact model for soft fingers [3]. M. R. Cutkosky [4], Nicholas Xydas and Imin Kao [3] continued with the conventional approach in their contact models. The conventional approach, however, is not able to provide answers to questions of area generated during contact, generation of forces and their distribution at the area of contact interface, and so on.

In this paper, modeling of the system dynamics during the soft contact interaction between a rigid body and a soft material is carried out using the Bond Graph technique and Finite Element method. The Finite Element method is convenient for static analysis, and can be employed to discretize the elastic continuum [5]. One can obtain characteristics of inertia, stiffness and damping, based on such discretization. The models are of special significance for (1) design and analysis for robotics hand development for dexterous manipulation, soft fingertips, etc., and (2) the control of robotic manipulation

II. FINITE ELEMENT ANALYSIS

The finite element method has become a powerful tool for the numerical solution of a wide range of engineering problems. In this method, a continuum is discretized into simple geometric shapes called *finite element*s. The main emphasis in this paper is to analyze the effect of soft material, specially the deformation of soft material under the action of contact forces[5]. The material properties and the governing relationships are considered over these elements and expressed in terms of unknown values at element corners. An assembly process, element connectivity, duly considering the loading and constraints, results in a set of equations. Solution of these equations gives us the approximate behavior of the continuum. After discretizing the region, finite element analysis (F.E.A.) of soft material is done to obtain the stiffness, mass, & damping matrices. The element stiffness and mass matrices can be calculated as[5]

$$k_e = t_e A_e B^T D B$$

$$I_e = \rho [N]^T [N] dV$$

Where *te* is the element thickness, *Ae* is the area of the element, *D* is the material property matrix, and, *B* is the element strain-displacement matrix. Using the element connectivity information, the global stiffness matrix can be calculated by placing the element stiffness matrix in the appropriate locations in the global matrix. By considering the minimum potential energy approach the Finite element equations are developed after a consistent treatment of the boundary conditions[5].

$$KQ = F$$

K is global stiffness matrix, *F* if global load vector and *Q* is the global displacement vector. In this paper, the Finite Element method is integrated with Bond graph for dynamic analysis of the soft material during contact interaction.

III. BOND-GRAPH MODELING

The Bond graph technique is especially convenient and computationally advantageous for dynamic analysis[6-8]. Bond graph is the pictorial representation of the dynamics of the system and are convenient for modeling of physical system dynamics in multiple energy domains as mentioned in table-1. A Bond graph model is based on the interaction of power between the elements. The method of Bond graphs is an attractive and powerful technique as it offers a unified framework for modeling the mechanism, and, the actuation and control systems due to its capability of handling multi-energy domains and depiction of cause and effect. Due to these advantages the Bond graph technique is used for modeling of soft contact.

Domain	Effort	Flow	Power
Mech. trans.	Force F	Velocity v	Fv
Mech. Rotation	Torque T	Angular Velocity ω	Tω
Hydraulic	Pressure P	Flowrate $\dot{Q}$	P$\dot{Q}$
Electro-Magnetic	Voltage e	Current i	ei

Table 1: Energy and power parameters

Stiffness, mass, & damping matrices obtained by F.E.A. will be used as C-field, I-field, & R-field in bond-graph.

IV. INTEGRATION BOND-GRAPH WITH F.E.A

Modeling of the system is done with Bond graph Technique. Bond graph is the pictorial representation of the dynamics of the system. Bond graphs are used for modeling of physical system dynamics in multiple energy domains. A bond graph model is based on the interaction of power between the elements. The bond graph technique was developed in 1959 by Professor Henry Paynter[6,7]. The method of Bond graphs is an attractive and powerful technique as it offers a unified framework for modeling the mechanism, and, the actuation and control systems due to its capability of handling multi energy domains[6-8]. Cause-effect relationships are also depicted and help in deriving the system equations in an algorithmic manner. Bond Graphs can be easily extended to nonlinear systems.

Sometimes the graphical representation of large physical systems becomes very complex if made by scalar bond graph. It is convenient and advantageous to have more compact representation. This compact graphical representation is called multi-bond graphs. A multibond is represented by a harpoon arrow made of two parallel lines and its bond strength is indicated in between them. In this paper, we depict the scalar bond by a thin harpoon arrow and the multibond with three scalar bonds by a thicker harpoon arrow. The strength 3 is not explicitly depicted on the graph in order to avoid clutter. Wherever the bond strength exceeds three, it is explicitly depicted on the multibond.

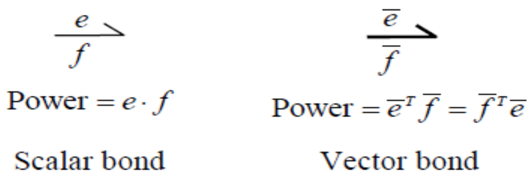

Fig. 1: Notation for scalar and multibonds

V. EXAMPLE

For checking the validity of the proposed model, an example of soft contact interaction is considered from a robotics perspective.

The soft material of dimensioning, length 0.05 m, thickness 0.01 m and width 0.005 m is considered. The soft material is divided into right angled triangular elements of base 0.0025mm and height 0.005 mm. Base of the soft material is assumed fixed. Under the action of normal force, the behavior and deformation of the material is analyzed. Using Finite Element Method the

force deformation relation is investigated. Finite Element method has been integrated with Bond graph for dynamic analysis.

MATERIAL: Silicon Rubber is considered as a soft material for analysis of soft modeling. Young modulus of elasticity (E) = 1000 N/m^2 and Poisson's ration (ν) = 0.48.

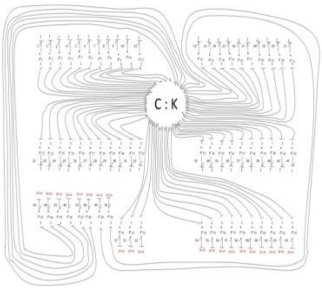

Fig. 3 C-field

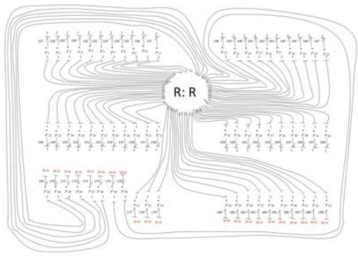

Fig. 4 R-field

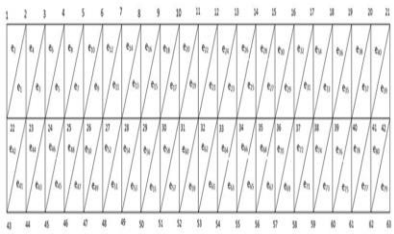

Fig. 2 Discretized

System equations are derived algorithmically from the Bond graph model. The MATLAB coding for simulations has been prepared directly from the bond-graph mode

VI.SIMULATION AND RESULT

The models have been tested through simulation. Simulation is done using MATLAB and results are discussed here. The total simulation time is taken as 10 seconds. The results are shown graphically at 10 intermediate instances of time.

CASE 1:- Here initially a point load of 2N is assumed acting on node 11, i.e 11th point of first layer. Deformation of the layer is analyzed at equal interval of time. This deformation of layers at different intervals of time is shown in Figure. The damping is also considered as R=10N·s/m.

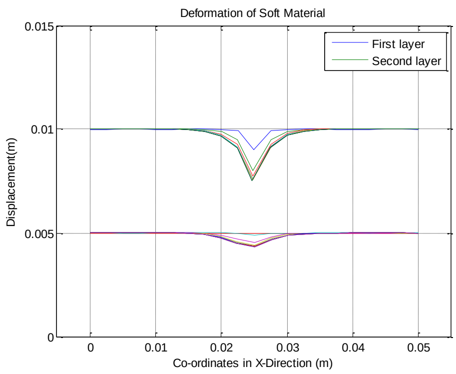

Fig. 5: Deformation of layer

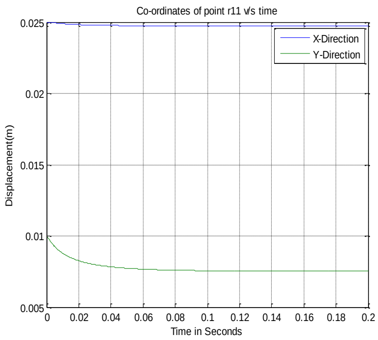

Fig. 6 Deformation of node 11

CASE 2:- Here initially a square block is assumed resting on soft material over the nodes 11 and 12 of first layer. Deformation of the layer is analyzed at equal interval of time. The damping is also considered as R=10N·s/m.

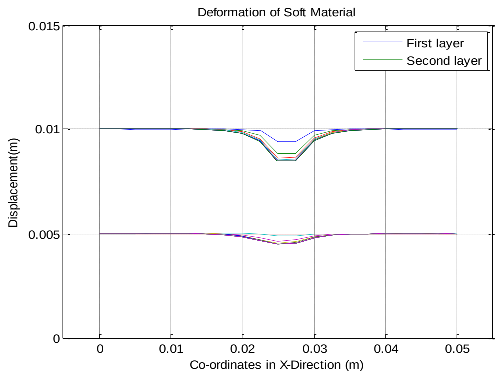

Fig. 7 Deformation of layer

CASE 3:- Here initially a cylinder is assumed resting on soft material over the nodes 11 of first layer. Deformation of the layer is analyzed at each time step. The damping is also considered as R=10N·s/m.

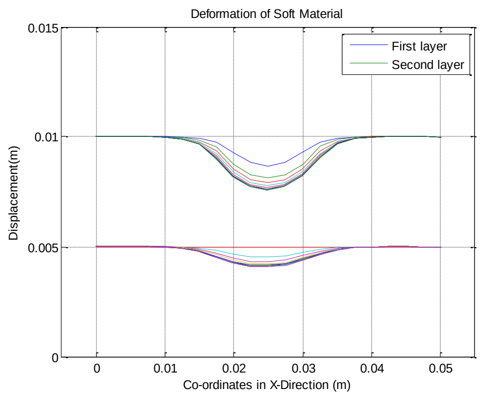

Fig. 8 Deformation of layer

VII.CONCLUSION

Modeling of contact interaction is one of the most important subjects in dexterous manipulation because grasping and manipulation are dictated by contact behavior. In case of soft contact, the contact force is distributed over an area of contact due to the effect of material compliance. Modeling of this aspect is indeed a challenging task.

- Modeling of soft material during contact interaction is carried out in this paper using Bond graphs.
- Finite Element Method is used for establishing *force-deformation relationship* during contact, as the deformation occurs when the rigid body interacts with soft material.
- The models have been tested through simulation. Simulation code has been developed using MATLAB and results are plotted, analyzed and discussed. During deformation of the material, the effect of compliance under compatibility conditions is observed.

REFERENCES

[1] D.C.Chang and Mark R. Cutkosky. "*Rolling with Deformable Fingertips*" presented in the International conference on Intelligent Robotic and Systems Aug 5-6, 1995.

[2] Nicholas Xydas and Imin Kao, "*Modeling of contact mechanics with Experimental result for soft fingers",* Proceeding of the 1998 IEEE/RSJ Intl. Conference on intelligent Robots and systems Victoria, B.C., Canada, October 1998, pp 488-493.

[3] Nicholas Xydas, Milind Bhagaval and Imin Kao, "*Study of soft ginger contact mechanics using finite elements analysis and Experiments",* Proceedings of the 2000 IEEE International Conference on Robotics and Automation San Francisco, CA, April 2000, pp 2179-2184.

[4] Anand Vaz and Shinichi Hirai, "*A simplified Model for a Biomechanical Joint with Soft Cartilage",* IEEE, 2004, pp 756-761.

[5] T. R. Chandrupatla and A. D. Belegundu , *"Introduction to Finite Elements in Engineering,"* Third Edition PHI, New Delhi, 2004.

[6] D.C.Karnopp, R.C.Rosenberg, D.L.Margolis, *System Dynamics: A Unified Approach,* John-Wiley and Sons Inc. New York, 1990.

[7] A. Mukherjee, and R. Karmakar, "*Modeling and Simulation of Engineering System through Bond Graphs*", Narosa Publishing House, New Delhi, 2000.

[8] www.bondgraph.com

[9] Paolo Tiezzi and Gabriele Vassura, "*Experimental Analysis of Soft fingertips with internal rigid core",* IEEE, 2005, pp 109-114.

[10] Anand Vaz, "*Bond Graph Modeling for Rigid Body Dynamics*" Lecture Notes on Rigid Body Dynamics.

[11] John J. Craig, *Introduction to Robotics: Mechanics & Control*, 2nd ed., Addison Wesley, 1989.

[12] T. R. Chandrupatla and A. D. Belegundu, "Introduction to Finite elements in Engineering", Third Edition, Prentice Hall of India Pvt. Ltd., New Delhi 2004.

[13] D. C. Karnoop, D. L. Margolis, and R. C. Rosenberg, "System Dynamics: A Unified Approach", 3rd edition (New York: John Wiley and Sons Inc. 2000).

[14] A. Mukherjee, and R. Karmakar, "*Modeling and simulation of Engineering System through Bond Graphs*", Narosa Publishing House, New Delhi, 2000.

[15] W. Borutzkt, G. Dauphin-Tanguy and J.U. Thoma, "*Advances in bond graph modeling: theory, software, applications",* Elsevier Science, 1995

[16] Dragan Antic, Biljana Vidojkovic and Miljana Mladenovic, "*An introduction to Bond Graph Modeling of Dynamics Systems"* IEEE, 1999.

[17] Anand Vaz and Anil Kumar Narwal, "*Multibond Graph Approach to the Analysis of Two Degree of Freedom Manipulator"*.