Soft Robot Dynamic Simulation Using Pseudo Rigid Body Model

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***Abstract*— While conventional rigid robots have been studied relatively widely, soft robots are considered difficult to fully understand its dynamic properties. Since soft robots consist of deformable materials with high compliance, it is generally more complex and costly to model with high fidelity. A means for modeling deformable materials that is more efficient than traditional finite element methods without sacrificing too much in the way of accuracy is demanded for the practical use of dynamic simulation of soft robots. In this paper, we extend conventional statically optimized Pseudo Rigid Body Model (PRBM) for modeling elastic multibody system to the dynamically optimized one by fitting the dominant natural frequencies to those of Absolute Nodal Coordinate Formulation (ANCF) dynamic model, resulting from finite element method. Using the proposed PRBM model, we were able to simulate vertical jumping motion of water strider robot and also optimize design parameters of the robot for maximal jumping height using our simulator.**

I. INTRODUCTION

Due to high flexibility and adaptability to tasks that conventional rigid robots are unable to accomplish, soft robots are considered to have high potential. The analysis of the kinematics and dynamics of compliant models is necessary for developing soft robot dynamic simulator; however it is challenging due to large nonlinear deflection which does not occur in rigid-body models. Pseudo-rigid-body model (PRBM) makes it possible to analyze compliant mechanisms simple and fast by approximating a compliant mechanism as a rigid-body mechanism, which can be analyze with classical theory. PRBM was first suggested by Howell [1] and further developed by Su [2] and Chen [3].

The objective function of the originally proposed PRBM is the difference between the tip deflection calculated by beam theory and PRBM. According to Chen [3], the static deflection of the optimized 3R PRBM by an external force has no big difference with the actual model. However, such statically optimized model shows non-negligible error for dynamic deflection under impact, which implies that it is inappropriate to be used as a general purpose soft robot dynamic simulator.

II. DYNAMICALLY OPTIMIZED PSEUDO RIGID BODY MODEL

In this paper, we consider the natural frequencies as a feature that represent dynamic property of a model. The natural frequency is the rate at which a system oscillates in the absence of any external force. Therefore, it is unique and invariant property of a model that does not depend on external factors. After investigating the natural frequencies of PRBM and absolute nodal coordinate formulation(ANCF) [4] model, one of the widely used finite element method to accurately simulate large deformation of flexible objects, we optimize the model parameters of PRBM so as to fit dominant natural frequencies to those of ANCF dynamic model.

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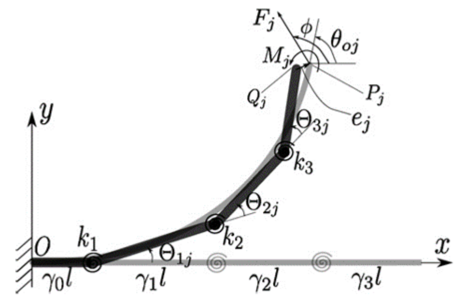

Fig. 1. The 3R pseudo-rigid-body model.

A. Natural Frequency in PRBM

PRBM is basically an open chain system with torsional spring at each of the joints as depicted in Fig. 1. The natural frequency can be obtained from its dynamic equation, generally written as follows:

$$M(\theta)\ddot{\theta} + N(\theta,\dot{\theta}) - K\theta = 0, \tag{1}$$

, where θ is the vector of the joint values and K is a diagonal matrix with its i-th diagonal element set as the torsional spring coefficient of the i-th joint.

Linearized dynamics of (1) is given by

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} &= \begin{bmatrix} \dot{\theta} \\ M^{-1}(\theta)\{-N(\theta,\dot{\theta}) - K\theta\} \end{bmatrix} \\ &= \begin{bmatrix} 0 & I \\ A & B \end{bmatrix}\begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} + H.O.T. \end{aligned}$$

where

$$A = \frac{\partial}{\partial\theta}[M^{-1}(\theta)\{-N(\theta,\dot{\theta}) - K\theta\}],$$
$$B = \frac{\partial}{\partial\dot{\theta}}[M^{-1}(\theta)\{-N(\theta,\dot{\theta}) - K\theta\}].$$

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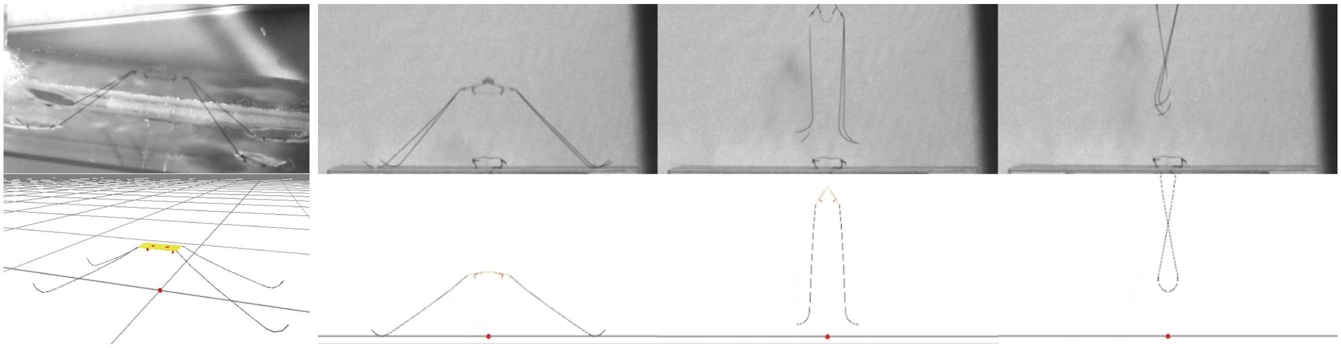

(a) (b)

Fig. 2. (a) A real water strider robot and a modeling of it, (b) Snapshot for jumping motion of water strider robot.

The natural frequencies of PRBM are the eigenvalues of $\begin{bmatrix} 0 & I \\ A & B \end{bmatrix}$. Since there exists multiple conjugate pairs of eigenvalues, the natural frequencies w_i are determined by the absolute values of them. In addition, the non-dimensionalized natural frequencies are

$$\hat{w}_i = w\sqrt{\frac{ml^3}{EI}}$$

, where m and l are mass and length of the whole model respectively; E is modulus of elasticity and I is moment of inertia.

B. Natural frequency of ANCF dynamic model

Dynamic equation of ANCF [4] is given by,

$$\begin{bmatrix} M & C_q^T \\ C_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_e \\ Q_d \end{bmatrix},$$

where M is the mass matrix of the system, C_q is the Jacobian matrix of the kinematic constraints. q is the vector of the system generalized coordinates, λ is the vector of Lagrangian multipliers, Q_e is the vector of forces that include external, gravity, Coriolis, centrifugal, and elastic forces, and Q_d is the vector resulting from the differentiation of the constraint equations.

Natural frequencies of such constrained dynamic system is given by finding solutions w to the following:

$$\det(\hat{K} - w^2\hat{M}) = 0$$

, where $\hat{K} = \begin{bmatrix} R & C_q^T \\ C_q & 0 \end{bmatrix}$, $\hat{M} = \begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix}$ and $R = \frac{\partial Q_e}{\partial q}$.

C. PRBM model parameter optimization based on natural frequency

The objective function to be minimized is set as,

$$e_D = \sum_i \sum_j \left(\frac{2\pi}{\hat{w}_{ij}^{PRBM}} - \frac{2\pi}{\hat{w}_{ij}^{ANCF}} \right)^2$$

, where $\hat{w}_{ij}^{PRBM}$ and $\hat{w}_{ij}^{ANCF}$ are the i-th dominant non-dimensionalized natural frequency of PRBM and ANCF model respectively at j-th pose.

III. CASE STUDY : WATER STRIDER ROBOT

Using the proposed PRBM, we developed the novel soft robot simulator based on multi-body dynamics simulator srLib (SNU Robotics Library). We modeled a water strider robot [5] and simulated jumping motion with this simulator as shown in Fig. 2. A water strider robot consists of a body, two legs, and two L-shaped cantilevers. Compliant parts of this robot, legs and L-shaped cantilevers, are modeled as dynamically optimized PRBM. Since the water environment does not exist in simulator, we simulated on a ground environment. The simulation result shows that not only the jumping height but also the series of motion is similar to a real robot experiment. This suggests that our soft robot simulator analyze dynamic motion, contact force, slip, collision of compliant system correctly. Furthermore, we optimized design parameters of the water strider robot to maximize the jumping height using our simulator.

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