An Integration of Contact Force Models with Multibody Dynamics Analyses for Human Joint Mechanisms and Effects of Viscoelastic Ground Contact

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Abstract

In human movement and rehabilitation analyses, human joint dynamics is a key to consider the incorporation of spring-damper components, flexible bodies and contact forces analytically. In the present study, an analytical method for human gaits were introduced to integrate those essential elements, and viscoelastic properties of musculoskeletal system were modeled with the absolute nodal coordination formula (ANCF) method representing flexible body motions. A contact force model simulates interactions between different body segments and the environment. The proposed system is applied to a slider crank mechanism, demonstrating its capabilities in human joint motion analysis using integrated dynamic model within the framework of multibody dynamics (MBD), which realizes dynamic/inverse dynamics for human biomechanics.

Keywords: Multibody dynamics (MBD), Contact force model, Absolute nodal coordinate formula (ANCF), human biomechanics

1. Introduction

Joint disorders progress irreversibly due to exercise and aging, and the number of patients who have joint disorders is increasing. These joint disorders affect gait and daily life [1] and they are one of the major issues in the current aging society. Physical therapy treatments for joint disorders include step-by-step treatment that restricts extension by restraining joints using joint orthosis, and rehabilitation that applies appropriate joint loads. From the viewpoint of prevention of the disease by joint load reduction, patient-specific order-made assistive devices using 3D printers and flexible materials [2] are also developing. However, the formulation of rehabilitation programs and the design of orthotics and assist devices are performed through subjective evaluations based on the experience of physical therapists and prosthetists. Therefore, the standard numerical evaluation index is needed, and modeling human joint mechanisms and analyzing their movements plays an important role in the formulation of the programs and design for the devices.

The dynamic and inverse dynamic analysis of human motion is possible with multibody dynamics (MBD) [3], [4], [5], [6], [7]. In order to reproduce the movement of a joint and analyze in detail the increase/decrease in the load that occurs on its components, it is necessary to construct and analyze models in which the muscles and ligaments are replaced with spring damper components or flexible bodies. The absolute nodal coordinate formula (ANCF) [8], [9], [10] has been proposed as an analysis method that incorporates finite element methods for systems composed of flexible bodies in MBD. The ANCF allows the analysis of systems that include large deformation of flexible bodies by dividing the body into multiple elements. Furthermore, by considering the effects of viscoelastic ground contact [11], [12], it becomes possible to analyze human motion such as human gait.

In this study, for the implementation of an analytical system for the joint load reduction analysis based on MBD, we demonstrate an integrated dynamic model by applying a flexible body, spring-damper components and ground contact force to the crank model and analyzing it dynamically.

2. Methodology

2.1. *Integrated dynamic analysis based on MBD*

The motion of a multibody system (MBS) composed of rigid bodies is described by a differential algebraic equation (DAE) such as Eq. (1) based on MBD theory using Lagrange multiplier λ and acceleration equation γ. Here, M_R, Φ_R and Q_R^A mean the mass matrix of rigid bodies, constraint matrix and external force vector respectively. Subscript q means the Jacobian matrix obtained by partially differentiating the constraint matrix with respect to the generalized coordinate matrix q.

$$\begin{bmatrix} M_R & \Phi_{Rq}^T \\ \Phi_{Rq} & 0 \end{bmatrix}\begin{bmatrix} \ddot{q}_R \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_R^A \\ \gamma \end{bmatrix} \quad (1)$$

Considering incorporating a flexible body into MBS, the generalized coordinate matrix of the flexible body is defined and its motion is described based on ANCF. According to Fig. 1, the generalized coordinate matrix of the flexible body i is described as Eq. (2) with *x*-*y* coordinates at each node and their slope [13].

$$q_F^i = \left[e_1^i, e_2^i, e_3^i, e_4^i, \cdots e_{4N_n-3}^i, e_{4N_n-2}^i, e_{4N_n-1}^i, e_{4N_n}^i\right]^T \quad (2)$$

The DAE of flexible multibody dynamics (fMBD) which incorporates flexible bodies based on ANCF can be expressed as Eq. (3) by expanding Eq. (1).

$$\begin{bmatrix} M_R & 0 & \Phi_{Rq}^T \\ 0 & M_F & \Phi_{Fq}^T \\ \Phi_{Fq} & \Phi_{Fq} & 0 \end{bmatrix}\begin{bmatrix} \ddot{q}_R \\ \ddot{q}_F \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_R^A \\ Q_F^A \\ \gamma \end{bmatrix} \quad (3)$$

Q_R^A and Q_F^A are external force vectors consist of gravity force and elastic force due to deformation of flexible body. When the analytical model consists of spring-damper components and the ground contact model, the total external force vector Q^A includes force vectors F_{SD} and F_c which are generated by spring-damper and viscoelastic ground contact as Eq. (4).

$$Q^A = \begin{bmatrix} Q_R^A \\ Q_F^A \end{bmatrix} + F_{SD} + F_C \quad (4)$$

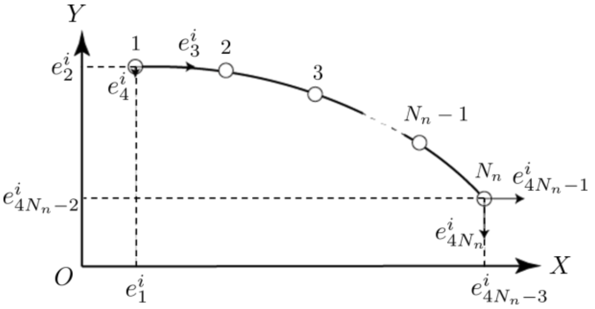

Fig. 1 The definition of the generalized coordinates of the flexible body I based on ANCF.

2.2. *Contact force in external force vector*

In the continuous contact model, the normal force F_N is expressed by Eq. (5) using the generalized stiffness parameter K and the relative penetration or indentation δ. Based on the theory of elasticity by Herts [11], the exponent n is equal to $2/3$.

$$F_N = K\delta^n \quad (5)$$

Considering the damping term, F_N can be written as follows with hysteresis damping factor χ. Here, c_r, $\dot{\delta}$ and $\dot{\delta}^{(-)}$ mean coefficient of restitution, relative approach/departing velocity and initial approach velocity respectively.

$$F_N = K\delta^n + \chi\delta^n\dot{\delta} \quad (6)$$

When χ is expressed as Eq. (7), substituting it into Eq. (6), F_N becomes Eq. (8).

$$\chi = \frac{3K(1 - {c_r}^2)}{4\dot{\delta}^{(-)}} \quad (7)$$

$$F_N = K\delta^n\left[1 + \frac{3(1 - Cr^2)}{4}\cdot\frac{\dot{\delta}}{\dot{\delta}^{(-)}}\right] \quad (8)$$

When sliding occurs in contact between the body and the ground, the dynamic friction force is described as Eq. (9) using kinetic friction coefficient μ, tangential velocity vector c_f and dynamic correction coefficient c_d based on friction velocity.

$$F_f = -\mu F_n c_f c_d \quad (9)$$

Consider the case where body i contacts the straight line $ax + by + c = 0$ at contact point *CP* according to Fig. 2, the coordinate and velocity at point cp are as Eq. (10).

$$\begin{cases} \begin{bmatrix} x_{cp} \\ y_{cp} \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \end{bmatrix} + \begin{bmatrix} r_i \\ 0 \end{bmatrix}\begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \\ \begin{bmatrix} \dot{x}_{cp} \\ \dot{y}_{cp} \end{bmatrix} = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} - \begin{bmatrix} r_i \\ 0 \end{bmatrix}\dot{\theta}_i \end{cases} \quad (10)$$

The relative penetration δ can be expressed as the shortest distance between the contact point and the straight line as Eq. (11).

$$\delta = \frac{\left|ax_{cp} + by_{cp} + c\right|}{\sqrt{a^2 + b^2}} \quad (11)$$

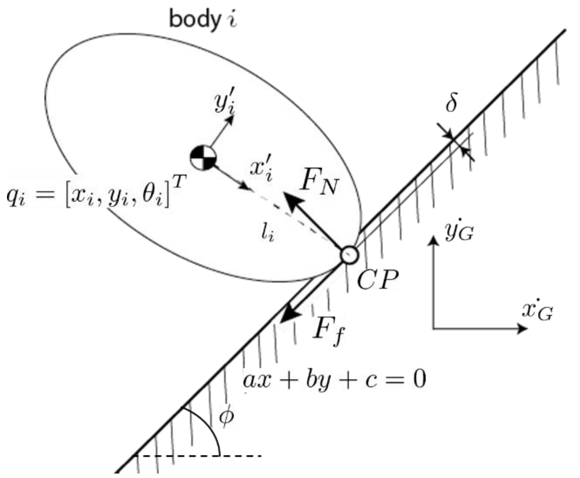

Fig. 2 Viscoelastic contact with the tilted ground described as $ax + by + c = 0$

Since the relative approach velocity $\dot{\delta}$ in Eq. (8) and tangential velocity c_r in Eq. (9) are perpendicular and parallel to the straight line, they can be written as Eq. (12) when the ground line moves as $[\dot{x}_G, \dot{y}_G]^T$. Here the angle between x-axis and the straight line is as $\varphi = tan^{-1}(-a/b)$.

$$\begin{aligned} \dot{\delta} &= (\dot{x}_G - \dot{x}_{cp}) \sin\varphi - (\dot{y}_G - \dot{y}_{cp}) \cos\varphi \\ c_r &= (\dot{x}_G - \dot{x}_{cp}) \cos\varphi + (\dot{y}_G - \dot{y}_{cp}) \sin\varphi \end{aligned} \tag{12}$$

2.3. *Slider-crank model for validation of integrated analysis*

In order to validate the MBD integrated analysis, a flexible body, a spring-damper component and the viscoelastic contact model are applied to the slider-crank model as shown in Fig. 3 to compare the changes in the behavior of the mechanism with and without these components. When N_e which is the number of division elements of the elastic beam F_1 based on ANCF is equal to 8, the kinematic constraint equation between F_1 and rigid links L_1 and L_2 of the slider-crank in Fig. 4 is described by Eq. (13).

$$\begin{bmatrix} \Phi^K_{L_1F_1} \\ \Phi^K_{L_2F_1} \end{bmatrix} = \begin{bmatrix} e_1 - x_1 - \frac{l_1}{2}\cos\theta_1 \\ e_2 - y_1 - \frac{l_1}{2}\sin\theta_1 \\ e_{33} - x_2 + \frac{l_2}{2}\cos\theta_2 \\ e_{34} - y_2 + \frac{l_2}{2}\sin\theta_2 \end{bmatrix} = 0 \tag{13}$$

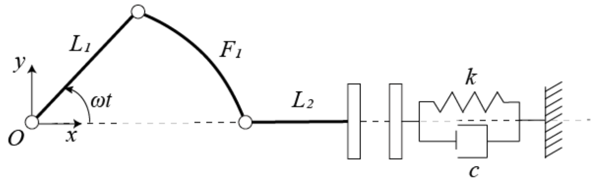

Fig. 3 Integrated dynamic model of slider crank

The driving constraint Φ^D is given to L_1 as Eq. (14) and angular velocity ω is equal to $2\pi/5\ [rad/s]$.

$$\Phi^D = \theta_1 - \omega t - \theta_1^{(0)} = 0 \tag{14}$$

In this slider-crank model, the endpoint at L_2 collides with L_3 and the effect of viscoelastic contact occurs without sliding. The contact force between these links is described as Eq. (15).

$$\begin{aligned} F_N &= K(x_3 - x_2)^{\frac{2}{3}}\left[1 + \frac{3(1 - {c_r}^2)}{4} \cdot \frac{\dot{x}_3 - \dot{x}_2}{\dot{\delta}^{(-)}}\right] \\ F_f &= 0 \end{aligned} \tag{15}$$

3. Results and Discussion

3.1. *Dynamic analysis of the integrated slider-crank model based on MBD*

Numerical analysis of the dynamic analysis based on MBD was performed by solving the DAE of the analytical system with MATLAB. In numerical computation, the fourth-order Runge-Kutta Gill's method [14] was used as the numerical integration method. The time step width is $h = 1.0 \times 10^{-5} [s]$. The parameters of spring-damper components are $k = 50, c = 0.1$ and the parameters of viscoelastic contact are $K = 4.0 \times 10^5, c_r = 0.1$ and $\mu = 0.45$. The results of the dynamic analysis for each element of the integrated slider-crank model are shown in Fig. 4. The x-coordinates of link L2 with and without flexible material are compared as shown in Fig. 5. The right graph in Fig. 5 shows the difference between each movement at first contact. When the model consists of a flexible body, the viscoelastic contact causes the deformation of it.

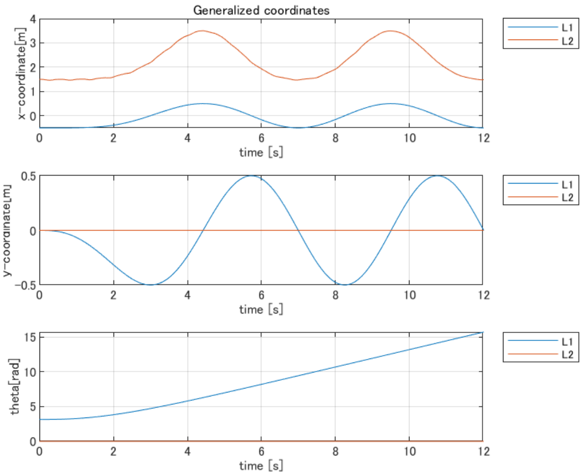

Fig. 4 The result of the dynamic analysis of the integrated slider-crank model.

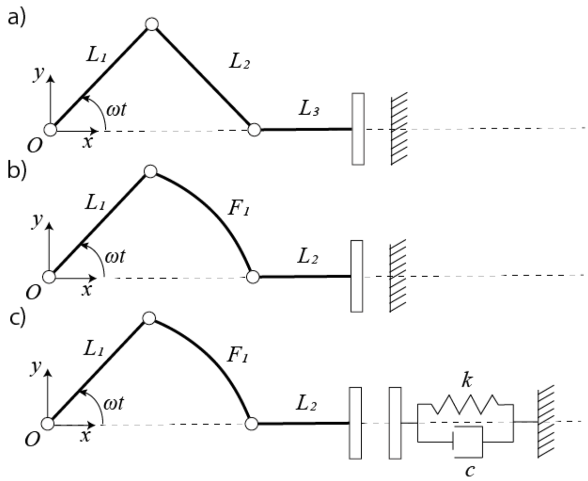

Fig. 6 Integrated dynamic models of slider crank. The model a) consists of rigid linkages, b) is replaced and has a flexible body and c) is applied with a flexible body and a spring-damper component.

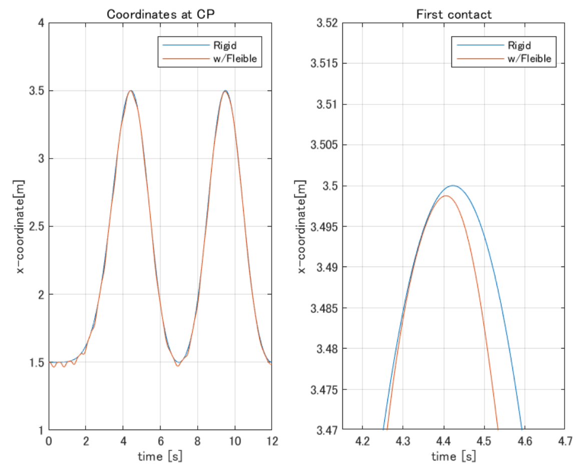

Fig. 5 The transition of x-coordinate at CP. The right graph is looking at the point in time when the effect of viscoelastic contact occurres.

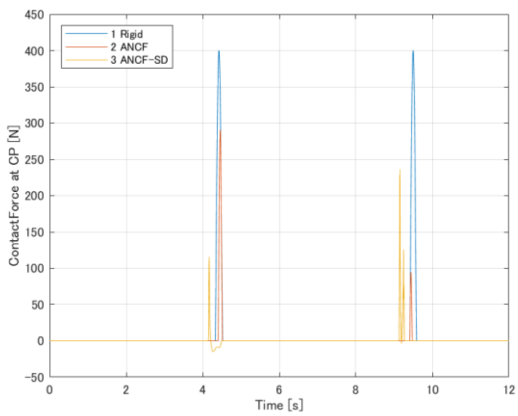

Fig. 7 The difference of contact force at contact point between the slider-crank models

3.2. *Constraint force by adopting viscoelastic contact model*

MBD-based dynamic analysis was performed for three models with different components in Fig. 6 to analyze the changes in contact force on the body of the analytical system. Fig. 7 shows the result of the dynamic analysis, and the deflection of the flexible body and the contraction of the spring-damper component reduces the relative penetration of the contact point, resulting in smaller contact forces compared to the rigid slider-crank model. It is possible to analyze the force by the viscoelastic contact which changes according to the components applied to the MBS.

4. Conclusion

Through this research, the integrated dynamic analysis of models which has contacts between objects or objects and ground was shown to be possible by expanding the analysis system to incorporate flexible bodies and a viscoelastic contact model. The use of flexible materials and spring-damper components in the joint mechanism enables gait analysis of walking robot legs that utilize nonlinear elastic properties and dynamic analysis of the effect of joint assistive devices on human walking motion, and is effective for the design and development of such robot legs and support devices. In further analysis, it is necessary to apply this integrated dynamic analysis to joint drive control for the robot leg models and the combination models of human gaits and assistive devices.

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