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Research Article

A MBD-Based Dynamic Analysis Framework with a Viscoelastic Contact Model and Flexible Elements Toward Human Power Assistive Devices

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ABSTRACT

It is important for the analysis of human movement and rehabilitation to incorporate spring-damper components, flexible materials, and contact force into the joint model considering human dynamics. In this study, the absolute nodal coordination formula (ANCF) method is introduced to the analytical model for the viscoelastic properties of the musculoskeletal system which is essential for analyzing human walking motion, and the flexible characteristics of the human body is reproduced. The consideration of a contact force model makes it possible to simulate contact actions between elements of the human body and the interaction with the environment. The proposed integrated framework is applied to multibody dynamics (MBD) based slider-crank mechanisms to demonstrate the dynamics/inverse dynamics analysis of human joint biomechanics.

1. Introduction

In the aging society, the increase in the number of patients with joint disorders is notable and it causes the need for nursing care/support due to difficulty walking or doing daily activities [1]. Step-by-step physical therapy treatments which use joint orthosis and restrict the range of the joint flexion and extension and rehabilitation which apply the appropriate loading on the joint are used to treat joint disorders and prevent their progression. In recent years, order-made physical assistive devices have been developed and provided using 3D printing technology and flexible materials [2], with the aim of preventing the disease by reducing the load on the joints. It is important to develop standard numerical evaluation indicators in order to ensure that the development of rehabilitation program and the prosthetics design and assistive tools are based on an objective, ergonomic perspective, rather than on the subjective evaluations that are based on the expert skills of physical therapists. In addition, modeling human joint mechanisms and analyzing their dynamics are essential for the adaptation for rehabilitation and design of the devices.

MBD [3], [4], [5], [6], [7] realize the dynamic/inverse dynamic analysis of human movements. Constructing the models that their muscles and related body parts are replaced with components with spring and damper properties as flexible bodies and analyzing them leads to a detailed analysis of the load increase/decrease on their components while reproducing the joint motions. ANCF [8], [9], [10] is the method that realizes the analysis including finite element methods for the multibody system (MBS) consisting of flexible bodies. The analysis of the system including large deformation generated by flexible bodies is allowed by divided bodies into multi-elements based on the ANCF, and the human gait analysis can be analyzed by considering viscoelastic contacts with the ground [11], [12].

In this study, we aimed to realize joint load reduction analysis by using the MBD scheme and implemented an analysis system by constructing an integrated dynamic model of a crank model that applies flexible bodies, spring-damper parts, and ground contact forces.

2. Methodology

2.1. *Integrated dynamic framework of MBD*

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In the analysis based on MBD, the coordinates of N rigid bodies that make up the analytical system are expressed by the generalized coordinate matrix q_R such as Eq. (1), and a differential algebraic equation abbreviated as DAE as Eq. (2) consisting of the motion equation and the acceleration equation γ describes the motion of MBS consisting of rigid bodies. Here, λ mean the Lagrange multiplier which uniquely determines the constraint forces and torques in the system, and M_R, Φ_R and Q_R^A means the mass matrix, Jacobian matrix of constraint equations and external force vector of the rigid system. The Jacobian is derived with the partially differentiation of the constraint matrix based on the generalized coordinate matrix of rigid bodies q_R.

$$\mathrm{q}_R = [q_1, q_2, \cdots, q_N]^T = [x_1, y_1, \theta_1, \cdots, x_N, y_N, \theta_N]^T \quad (1)$$

$$\begin{bmatrix} M_R & \Phi_{Rq}^T \\ \Phi_{Rq} & 0 \end{bmatrix} \begin{bmatrix} \ddot{q}_R \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_R^A \\ \gamma \end{bmatrix} \quad (2)$$

When flexible bodies are incorporated into the MBS based on ANCF theory, the generalized coordinate matrix is defined for the flexible body i is defined as Eq. (3). It consists of *x-y* coordinates and displacement gradient [13] at each node as shown in Fig. 1.

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

When the MBS includes flexible bodies based on ANCF, the DAE of flexible multibody dynamics (fMBD) can be expanded as Eq. (4) from Eq. (2).

$$\begin{bmatrix} M_R & 0 & \Phi_{Rq}^T \\ 0 & M_F & \Phi_{Fq}^T \\ \Phi_{Fq} & \Phi_{Fq} & 0 \end{bmatrix} \begin{bmatrix} \ddot{q}_R \\ \ddot{q}_F \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_R^A \\ Q_F^A \\ \gamma \end{bmatrix} \quad (4)$$

Q_R^A in Eq. (4) mean the external force vectors consisting of gravity. Q_F^A is elastic force of flexible bodies. When the MBS includes components with spring and damper systems and the ground contact model and the bodies receive forces from them, spring-damper force vectors

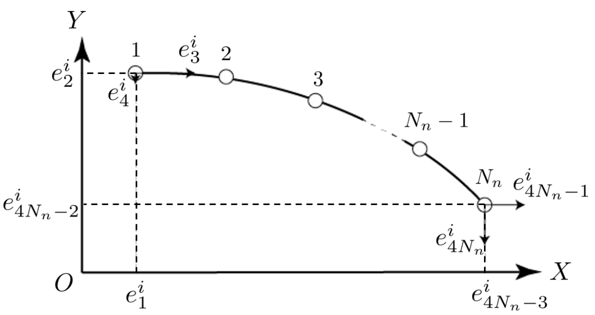

Fig. 1 In the flexible body I, ANCF provides this generalized coordinates.

F_{SD} and viscoelastic contact force vector F_c are added to the entire external force vector Q^A as Eq. (5).

$$Q^A = \begin{bmatrix} Q_R^A \\ Q_F^A \end{bmatrix} + F_{SD} + F_C \quad (5)$$

2.2. *Definition of contact force in MBS*

On the theory of Herts's continuous contact model [11] as shown in Eq. (6), the normal force is represented as F_N with the generalized stiffness parameter K and the amount of the relative penetration δ to the power of $\mathrm{n} = 2/3$.

$$F_N = K\delta^n \quad (6)$$

Eq. (7) shows the normal force considering the damping term which uses the hysteresis damping factor χ.

$$F_N = K\delta^n + \chi\delta^n\dot{\delta} \quad (7)$$

χ is expressed as Eq. (8) using a restitution coefficient c_r, relative approach and departing velocity $\dot{\delta}$ and initial approach velocity $\dot{\delta}^{(-)}$, and F_N can be represented by substituting χ into Eq. (7) as Eq. (9).

$$\chi = \frac{3K(1 - {c_r}^2)}{4\dot{\delta}^{(-)}} \quad (8)$$

$$F_N = K\delta^n \left[1 + \frac{3(1 - Cr^2)}{4} \cdot \frac{\dot{\delta}}{\dot{\delta}^{(-)}}\right] \quad (9)$$

Tangential force is generated as the dynamic friction force when slippage occurs during contact between the body and the ground. It is described as Eq. (10) using µ, c_f and c_d which means kinetic coefficients on friction, tangential velocity vector and dynamic correction respectively.

$$F_f = -\mu F_n c_f c_d \quad (10)$$

When body i contacts the straight line expressed by the equation; $\mathrm{a \cdot x + b \cdot y + c = 0}$ defined at contact point CP, the coordinate and velocity at CP shown in Fig. 2 are described as Eq. (11) using rotation matrix.

$$\begin{cases} \begin{bmatrix} x_{cp} \\ y_{cp} \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \end{bmatrix} + \begin{bmatrix} r_i \\ 0 \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \\ \begin{bmatrix} \dot{x}_{cp} \\ \dot{y}_{cp} \end{bmatrix} = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} - \begin{bmatrix} r_i \\ 0 \end{bmatrix} \dot{\theta}_i \end{cases} \quad (11)$$

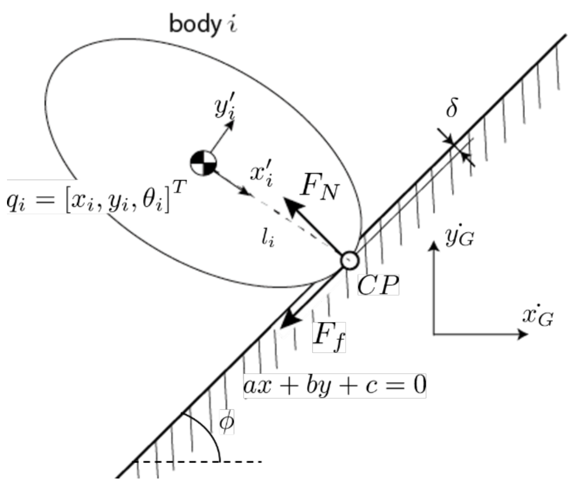

Fig. 2 Definition of contact with a viscoelasticity for ground with a certain slope

The formula for finding the minimum distance between a line and appoint as Eq. (12) can derive the relative penetration δ.

$$\delta = \frac{|ax_{cp} + by_{cp} + c|}{\sqrt{a^2 + b^2}} \tag{12}$$

Considering the movement of the ground moving at a speed of $[\dot{x}_G, \dot{y}_G]^T$, relative approach velocity $\dot{\delta}$ which is vertical speed relative to the ground and tangential velocity c_r can be expressed as Eq. (13) with the slope angle of the ground $\varphi = tan^{-1}(-a/b)$.

$$\begin{aligned} \dot{\delta} &= (\dot{x}_G - \dot{x}_{cp}) \sin\varphi - (\dot{y}_G - \dot{y}_{cp}) \cos\varphi \\ c_r &= (\dot{x}_G - \dot{x}_{cp}) \cos\varphi + (\dot{y}_G - \dot{y}_{cp}) \sin\varphi \end{aligned} \tag{13}$$

2.3. *A model for validation of integrated analysis focusing on the slider-crank system*

The integrated slider crank model (Fig. 3) is constructed with a flexible body including components with a spring-damper system, and the contact model with a viscoelasticity for validation of the integrated MBD analysis, and the variation of the mechanism behavior with and without these three components is compared. By dividing the elastic beam F_1 into 8 elements based on the flexible element division of ANCF, the kinematic constraint equation between the rigid beams and the flexible beam in Fig. 4 is written as Eq. (14).

$$\begin{bmatrix} \Phi^K_{L_1F_1} \\ \Phi^K_{L_2F_1} \end{bmatrix} = \begin{bmatrix} e_1 - x_1 - \frac{l_1}{2}\cos\theta_1 \\ e_2 - y_1 - \frac{l_1}{2}\sin\theta_1 \\ e_{33} - x_2 + \frac{l_2}{2}\cos\theta_2 \\ e_{34} - y_2 + \frac{l_2}{2}\sin\theta_2 \end{bmatrix} = 0 \tag{14}$$

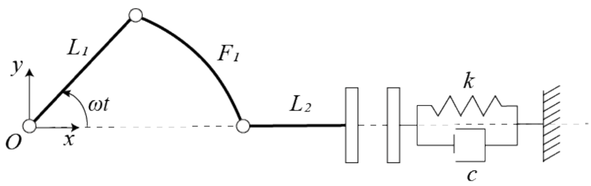

Fig. 3 A slider crank model in an integrated way

The driving or moving constraint Φ^D consisting of and angular velocity ω as Eq. (15) is applied to link L_1. Here, $\omega = 2\pi/5\ [rad/s]$.

$$\Phi^D = \theta_1 - \omega t - \theta_1^{(0)} = 0 \tag{15}$$

In this analytical model, the y-axis velocity at the contact point is always 0 and no slip occurs, so the viscoelastic contact force can be expressed as Eq. (16).

$$\begin{aligned} F_N &= K(x_3 - x_2)^{\frac{2}{3}} \left[1 + \frac{3(1 - {c_r}^2)}{4} \cdot \frac{\dot{x}_3 - \dot{x}_2}{\dot{\delta}^{(-)}}\right] \\ F_f &= 0 \end{aligned} \tag{16}$$

3. Results and Discussion

3.1. *Result and comparison of Dynamic analysis based on MBD*

In this computational experiment, numerical calculations for MBD-based dynamic analysis were carried out by solving the DAE of the system using Runge-Kutta Gill's method [14], which is a fourth-order explicit numerical integration method. Here, the time step is given by $h = 1.0 \times 10^{-5} [s]$ as the time resolution in the computer experiment. The parameters of components with spring and damper systems and viscoelastic contact are given as $k = 50, c = 0.1$, $K = 4.0 \times 10^5, c_r = 0.1$ and $\mu = 0.45$. Fig. 4 shows the transition of the generalized coordinates of the rigid links as the result of the dynamic analysis on the slider-crank model in an integrated way. Fig. 5 shows a comparison of the x-coordinates at the contact point CP on the link L2 depending on whether flexible beams are applied. An enlarged graph of the contact timing is shown as the right graph in Fig. 5.

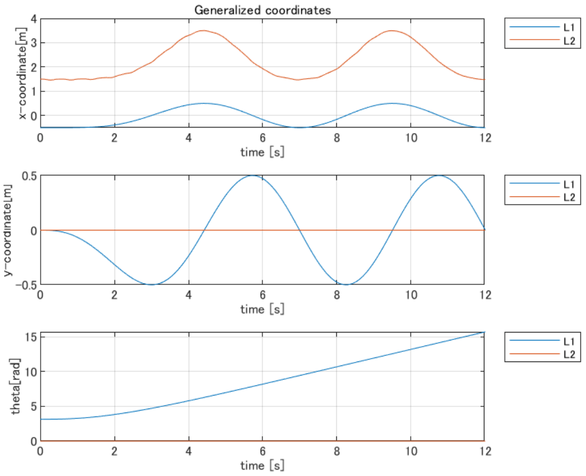

Fig. 4 The transition of the generalized coordinates of the rigid links.

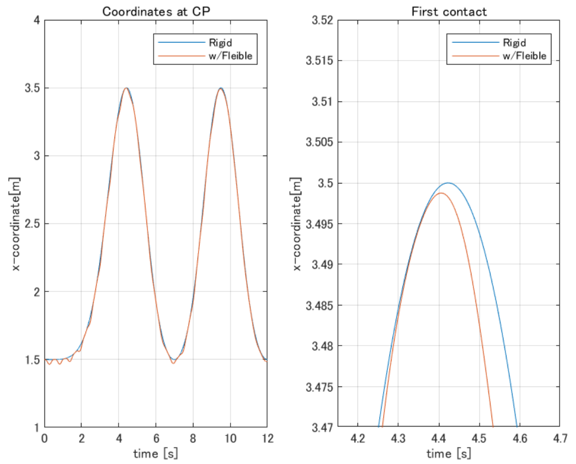

Fig. 5 Difference in x-coordinate of contact point with and without flexible beam.

3.2. *Difference of viscoelastic contact force by adopting components in analytical system*

The results of comparing the contact force in the negative x-axis direction that occurs on the CP in three models that have the different combinations of parts shown in Fig. 6 inserted is shown in Fig. 7. The relative amount of penetration is reduced due to the deformation of the flexible body and the contraction of the spring damper parts, and the contact force is smaller than that of the simple rigid slider link model, making it possible to control and analyze viscoelastic contact based on MBD by parts applied to MBS.

4. Conclusion

According to the enlargement of the analytical system with flexible bodies and the contact model with a viscoelasticity, this study shows that it is possible to analyze dynamically integrated models including the

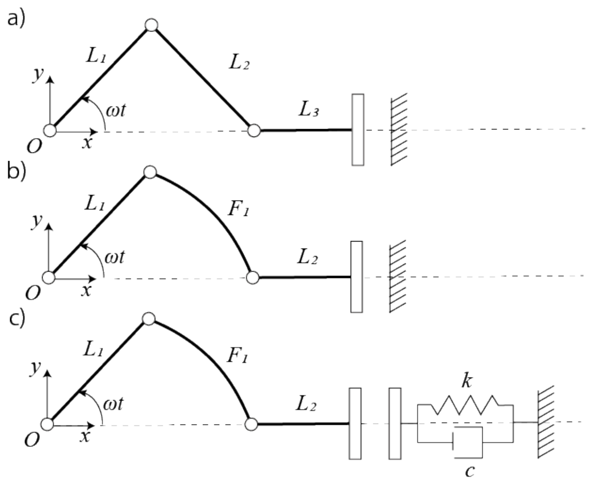

Fig. 6 Integrated slider-crank contact model. a) is rigid linkage model, b) includes a flexible beam and c) consist of a spring-damper systems.

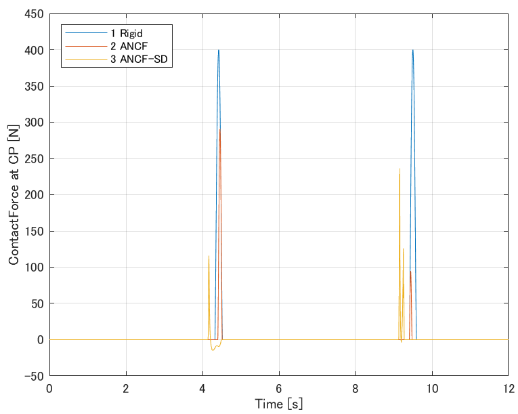

Fig. 7 The changes in contact force due to differences in elements of the slider-crank model.

contacts between objects or between object and ground. From the realization of the analysis of joint mechanisms using materials with a flexibility as spring and damper components, the gait analysis of walking robot legs and the dynamic analysis of joint assist devices that make use of nonlinear elastic properties can be enabled, and it is valid for the design and robot leg developments and human power assistive devices. In more analysis, this integrated dynamic analysis is important to control rotations of joints attached in the robot leg mechanisms Even in the complex model, human gait and assistive device can be modeled.

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References

1. J. W. Michael, K. U. Schlüter-Brust, and P. Eysel, "The epidemiology, etiology, diagnosis, and treatment of osteoarthritis of the knee," Dtsch Arztebl Int. 2010 Mar; 107(9): pp. 152-62.
2. T. A. M. Oud, E. Lazzari, H.J. H. Gijsbers, M. Gobbo, F. Nollet, and M. A. Brehm, "Effectiveness of 3D-printed orthoses for traumatic and chronic hand conditions: A scoping review," PLoS ONE 16(11): e0260271, 2021.
3. W. Schiehlen, N. Guse, and Robert, Seifried, "Multibody dynamics in computational mechanics and engineering applications," Computer Methods in Applied Mechanics and Engineering, Vol. 195(41-43), pp. 5509-5522, 2006.
4. Nikravesh, P.E. (2004). An Overview of Several Formulations for Multibody Dynamics. In: Talabă, D., Roche, T. (eds) Product Engineering. Springer, Dordrecht. https://doi.org/10.1007/1-4020-2933-0_13
5. P. Eberhard, W. Schiehlen, "Computational Dynamics of Multibody Systems: History, Formalisms, and Applications," J. Comput. Nonlinear Dynam. Jan 2006, Vol. 1(1): pp. 3-12.
6. W. Schiehlen, "Computational dynamics: theory and applications of multibody systems," European Journal of Mechanics - A/Solids, Vol. 25(4), pp. 566-594, 2006.
7. J. Baumgarte, "Numerical stabilization of the differential equations of Keplerian motion," *Celestial Mechanics* Vol.**5**, pp. 490–501, 1972.
8. J. Gerstmayr, H. Sugiyama, and A. Mikkola, "Review on the Absolute Nodal Coordinate Formulation for Large Deformation Analysis of Multibody Systems," *J. Comput. Nonlinear Dynam*. Jul 2013, 8(3): 031016.
9. A. A. Shabana, and R. Y. Yakoub, "Three Dimensional Absolute Nodal Coordinate Formulation for Beam Elements: Theory," *J. Mech. Des*. Dec 2001, 123(4): 606-613.
10. V. Gufler, E. Wehrle, and A. Zwölfer, "A review of flexible multibody dynamics for gradient-based design optimization", *Multibody Syst Dyn* **53**, 379–409 (2021).
11. M. Machado, P. Moreira, P. Flores, H. M. Lankarani, "Compliant contact force models in multibody dynamics: Evolution of the Hertz contact theory," Mechanism and Machine Theory, Vol. 53, July 2012, pp. 99-121.
12. J. Alves, N. Peixinho, M. T. Silva, P. Flores, and H. M. Lankarani, "A comparative study of the viscoelastic constitutive models for frictionless contact interfaces in solids," Mechanism and Machine Theory, Vol. 85, March 2015, pp. 172-188.
13. A. A. Shabana, "Flexible Multibody Dynamics: Review of Past and Recent Developments," *Multibody System Dynamics* **1**, 189–222 (1997).
14. J. C. Butcher, and G. Wanner, "Runge-Kutta methods: some historical notes," Applied Numerical Mathematics, Vol. 22, pp. 113-151, 1996.

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