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Dynamic simulations of electromechanical robotic systems driven by DC motors

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SUMMARY

When modeling the dynamics of robotic systems containing electric motors, the force generated by the motor is generally considered only as an applied torque or force that is independent of mechanical state variables such as velocity. Due to the electromechanical coupling effects in the motors, this approach leads engineers working on a robotic system to designing faulty controllers. In this paper, we propose a dynamics analysis model in which DC motor dynamics are embedded into a mechanical dynamics model such that the electromechanical coupling effects are included in the overall model. A model for the DC motor is developed based on its equivalent circuit model and incorporated into the generalized recursive dynamics formula previously developed by our group. The resulting dynamic numerical simulation program provides an effective and realistic approach for analyzing the electromechanical dynamics of robotic systems driven by DC motors. The developed numerical simulation tool is evaluated by applying to an industrial robot and a flexible antenna system driven by DC motors for a satellite.

KEYWORDS: Electromechanical coupling; Recursive dynamics formula; Analysis of robot dynamics.

NOMENCLATURE

Y	Cartesian velocity vector
q	Relative coordinate vector
B	Jacobian matrix
δZ	Virtual displacement
M	Mass Matrix
Φ	Joint constraint Matrix
λ	Lagrange multiplier
Q	Generalized force vector
V_t	Input voltage of a DC motor
I_a	Armature current of a DC motor
R_a	Armature resistance of a DC motor
L_a	Armature circuit inductance of a DC motor
E_a	Armature voltage of a DC motor
T_{out}	Generated torque of a DC motor
ω	Angular velocity of a DC motor shaft
V_{in}	Input voltage of a DC motor driver
i_m	Circuit current of a DC motor driver
R_m	Total load of a DC motor
i_1	Feedback current of a DC motor driver
A	Gain of a DC motor driver
R_1	Circuit resistance of a DC motor driver

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1. INTRODUCTION

Dynamics analysis software is used to simulate the dynamical motions of real mechanical systems. This software has been used to aid the design of various mechanical systems, including factory robotic systems, factory machinery, and transportation systems.[1–3] Most of these mechanical systems are driven by electrical motors. Such motors are subject to electromechanical coupling effects,[4] which cause electrical variables (e.g. voltage, current) to affect mechanical variables (e.g. velocity, torque) and *vice versa*. However, existing programs for the dynamic simulation of mechanical systems containing motors do not explicitly account for the electromechanical coupling effects inside the motors; they simply model the effect of the motor as an applied torque or force. This simplified model can adequately simulate the behavior of real systems when the electric driver and controller for the motor have sufficient driving power and responsiveness to guarantee a linear relation between the electrical input and the torque generated by the motor.[5] However, the simplified model sometimes breaks down when modeling systems in which the driving power of the electric driver/controller is sufficiently low that the electromechanical coupling effects in the motor cannot be neglected. Extension of the simplified model to include the electromechanical coupling effects of the electric motor yields a model that can correctly simulate the dynamic behavior of a robotic system with electric motors. Hence, such a simulation program for the dynamics of multi-body robotic systems that contain a motor as a dynamic component would aid in understanding the dynamical behavior of these systems and would be an indispensable tool in the design of systems containing electric motors. For example, simulations of industrial robot systems with electric motors can assist in the selection of motors that give the desired motion or power of the robot arms.[6] In addition, an efficient control law can be developed using the simulation tool because it provides controller designers with a more realistic plant model.

To include electromechanical coupling effects in a dynamic simulation of a system containing electric motors, the force changes due to electromagnetic fields, as well as the changes in the electromagnetic fields, should be modeled and solved at the same time as solving the changes in other mechanical variables of the system. One way to achieve this is to develop a motor model that can be integrated into the finite element formulation of mechanical systems.[7] Although this approach gives flexible and precise simulation models, it entails long calculation times and is inadequate for dynamic simulations because of difficulties in formulations with large displacements of the model. Another approach is to treat electric motor as a component base on the equivalent circuit model for a motor, which can be simulated with ordinary differential equations (ODEs). Because this model can be embedded into an existing multibody dynamics simulation program and all of the state equations of the dynamics model are ODEs, this approach drastically reduces the calculation times. Moreover, this approach can successfully simulate the dynamical behavior of systems with motors under conditions in which the simplified approach neglecting electromechanical coupling effects fails to correctly simulate the system response. Importantly, because the motor parameters of the equivalent circuit model can be set to values determined in experiments on the real electrical motor, the model can be tuned to the real system.

In a previous study, we developed a generalized recursive formula[8] that minimizes relative generalized coordinates and constraint equations about joint variables. When included into a multi-body dynamics simulation program, the proposed formula enabled more stable analysis and reduced simulation times.[3] In the present study, we extended the recursive dynamics formula to model a mechanical system containing an electric DC motor, one of the most popular electrical motors. To achieve this, we added the mathematical model of a DC motor constructed from its equivalent circuit model to the generalized recursive dynamic algorithm. The resulting simulation program was sufficiently compact that it could be run on a PC and yet efficient enough to provide simulation results for a complex system in a reasonable time. The developed software was found to realistically simulate the behavior of systems containing DC motors. The capabilities and usefulness of the developed program were illustrated through simulations of two robotic systems containing a DC motor: an industrial robot system and a flexible satellite antenna.

2. RECURSIVE FORMULATION OF MULTI-BODY DYNAMICS

The state equations for the analysis of the dynamics of a multi-body system can be based either on an absolute coordinate system or on the relative coordinates of independent joints.[9] In a previous paper, we developed a dynamics analysis algorithm based on joint variables of relative coordinates.[8] We now extend that algorithm to the modeling of systems containing electrical DC motor elements. Below we briefly explain the base equations of the dynamic analysis algorithm based on joint variables of relative coordinates.

The relation between Cartesian velocity $Y \in R^{nc}$ and relative coordinate vector $q \in R^{nc}$ can be expressed as follows:

$$Y = B\dot{q} \tag{1}$$

where B is a Jacobian matrix that includes only functions of relative coordinates of the joints between body elements. In Eq. (1), Y and $\dot{q}$ can be expressed as follows:

$$Y = \left[Y_0^T, Y_1^T, Y_2^T, \ldots, Y_n^T\right]_{nc\times 1}^T \tag{2}$$

$$\dot{q} = \left[Y_0^T, \dot{q}_1^T, \dot{q}_{12}^T, \ldots, q_{(n-1)n}^T\right]_{nr\times 1}^T \tag{3}$$

where Y_i denotes the Cartesian velocity of body i and $\dot{q}_{jk}$ represents the relative coordinate vector between body j and body k. Similarly, the recursive relationship between virtual displacements can be expressed as follows:

$$\delta Z = B\delta q \tag{4}$$

where δZ is the virtual displacement vector in the Cartesian coordinate system ($Z \in R^{nc}$) and δq is the virtual displacement vector in the relative coordinate system. A more detailed explanation of this formulation can be found in reference [8].

The variational form of the Newton-Euler equations of motion for a constrained mechanism is

$$\delta Z^T\left(M\dot{Y} + \Phi_z^T\lambda - Q\right) = 0 \tag{5}$$

where δZ must be kinematically admissible for all joints except cut joints,[10] and $\Phi \in R^{nm}$ and λ denote the joint constraint and the corresponding Lagrange multiplier, respectively. The mass matrix M and the generalized force vector Q are defined as

$$M = diag(M_1, M_2, \ldots, M_{nbd}) \tag{6}$$

$$Q = \left(Q_1^T, Q_2^T, \ldots, Q_{nbd}^T\right) \tag{7}$$

where the subscript nbd is the number of body elements of the analysis model. Substituting the virtual displacement relationship into Eq. (5) yields

$$\delta q^T\left\{B^T\left(M\dot{Y} + \Phi_z^T\lambda - Q\right)\right\} = 0 \tag{8}$$

Since δq is arbitrary, the following equations of motion are obtained:

$$F = B^T\left(M\dot{Y} + \Phi_z^T\lambda - Q\right) = 0 \tag{9}$$

The state equations for a dynamic system can be constructed by combining the equations of motion, $F = 0$ as in Eq. (9), the constraint equations, $\Phi(q, t)$, the relationship between the velocity and displacement, $\dot{q} = v$, and, the relationship

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between the acceleration and velocity, $\dot{v} = a$, as follows[11]:

$$\begin{bmatrix} F(q, v, a, \lambda, t) \\ \Phi(q, t) \\ \dot{\Phi}(q, v, t) \\ \ddot{\Phi}(q, v, a, t) \\ \dot{q} - v \\ \dot{v} - a \end{bmatrix} = 0 \qquad (10)$$

Application of the 'tangent space method' described in Ref. 12 to Eq. (10) yields the following nonlinear system that must be solved at each time step:

$$H(p_n) = \begin{bmatrix} F(q_n, v_n, a_n, \lambda_n, t_n) \\ \Phi(q_n, t_n) \\ \dot{\Phi}(q_n, v_n, t_n) \\ \ddot{\Phi}(q_n, v_n, a_n, t_n) \\ U_0^T(q_n + \beta_0 v_n + \beta_1) \\ U_0^T(v_n + \beta_0 a_n + \beta_2) \end{bmatrix} = 0 \qquad (11)$$

where

$$p_n = \left[q_n^T, v_n^T, a_n^T, \lambda_n^T\right] \qquad (12)$$

and β_0, β_1, and β_2 are the coefficients of the backward difference formula (BDF). Let U_0 be a $R^{nr} \times R^{(nr\text{-}nm)}$ matrix chosen such that the augmented square matrix $[U_0, \Phi_q^T]^T$ is nonsingular. The nonlinear equations in Eq. (11) can be solved by using Newton's method and a library of generalized recursive formulas.[8]

3. A SIMULATION MODEL OF ELECTRIC DC MOTORS

In order to model interactions between mechanical state variables (e.g., velocity and torque) and electrical state variables (e.g., voltage and current), an appropriate model of the motor that includes the electromechanical coupling effects must be incorporated into the dynamic simulation model. Thus, an appropriate model of an electric DC motor must be developed. One such model, which is well-defined and widely accepted, is the equivalent circuit model. Before describing how this is done, we first present a brief description of the equivalent circuit model of a motor.

Provided the magnetic field flux from the stator of a motor is constant with time and the voltage drift induced by the brush of the motor is negligibly small, the dynamic behavior of the motor can be simulated using the equivalent circuit including a resistor, an inductor, and a capacitor. The governing equation of this circuit is as follows:[13]

$$V_t = E_a + I_a R_a + L_a \frac{dI_a}{dt} \qquad (13)$$

where R_a and L_a are the armature resistance and the armature circuit inductance, respectively, and $L_a \frac{dI_a}{dt}$ represents the transient effects generated by commutator segments when a brush shorts out.[14] For general DC motors, the armature voltage can be expressed as:[13]

$$E_a = K_a \times \omega \qquad (14)$$

where K_a is referred to as the unification constant determined by experiments. By the equation derived from the equivalent energy relation between electrical and mechanical energies,

$$T_{out} = K_b \times I_a \qquad (15)$$

where T_{out} is the output torque exerted by the motor and K_{out} is a experimental constant.

4. EXTENDED FORMULA FOR IMPLEMENTING DC MOTOR

As mentioned in Section 3, the equivalent circuit model for a DC motor is to be incorporated into a previously developed computer simulation program for multi-body dynamics based on the relative coordinates of joints. The challenge is to formulate the relation between the motor parameters of the equivalent circuit model and the dynamical parameters of the multi-body mechanical model and to implement the formulae for the equivalent circuit model into the simulation program for multi-body dynamics.

To derive the extended version of the previously developed equations for dynamical analysis, Eq. (1) is substituted into Eq. (9) to yield:

$$F = (B^T M B)\ddot{q} + \Phi_q^T \lambda - B^T Q = 0 \qquad (16)$$

From the electrical characteristics of a DC motor, and taking $I_a = \hat{q}$, the equivalent circuit formula of the j-th motor implemented at the k-th joint is constructed as follows:

$$\bar{F}_j = E_{a\_j} + R_{a\_j}\dot{\bar{q}}_j + L_{a\_j}\ddot{\bar{q}}_j - V_{t\_j} = 0 \qquad (17)$$

or

$$\bar{F}_j = K_{ak}\phi_k \dot{q}_j + R_{aj}\dot{\bar{q}}_j + L_{aj}\ddot{\bar{q}}_j - V_{tj} = 0 \qquad (18)$$

Since one DC motor state variable corresponds to one joint variable, we can see that $k = j$. This electromechanical coupling equation is directly affected by the joint variable q, and the output torque of the j-th DC motor acting on the k-th joint variable is

$$\bar{Q}_k = K_{a\_j}\phi_j \bar{q}_j \qquad (19)$$

When the number of DC motors in the entire system is np, $\bar{F} \in R^{np}$, and the equation for the total system $F_{tot} \in R^{nr+np}$ is

$$\begin{aligned} F_{tot} &= \begin{bmatrix} F \\ \bar{F} \end{bmatrix} \\ &= \begin{bmatrix} (B^T M B)\ddot{q} + \Phi_q^T \lambda - B^T Q \\ (K_a\phi)_{diag\_m}\dot{q}_k + (R_a)_{diag\_m}\dot{\bar{q}} + (L_a)_{diag\_m}\ddot{\bar{q}} - (V_t)_{vec} \end{bmatrix} \\ &= 0 \end{aligned} \qquad (20)$$

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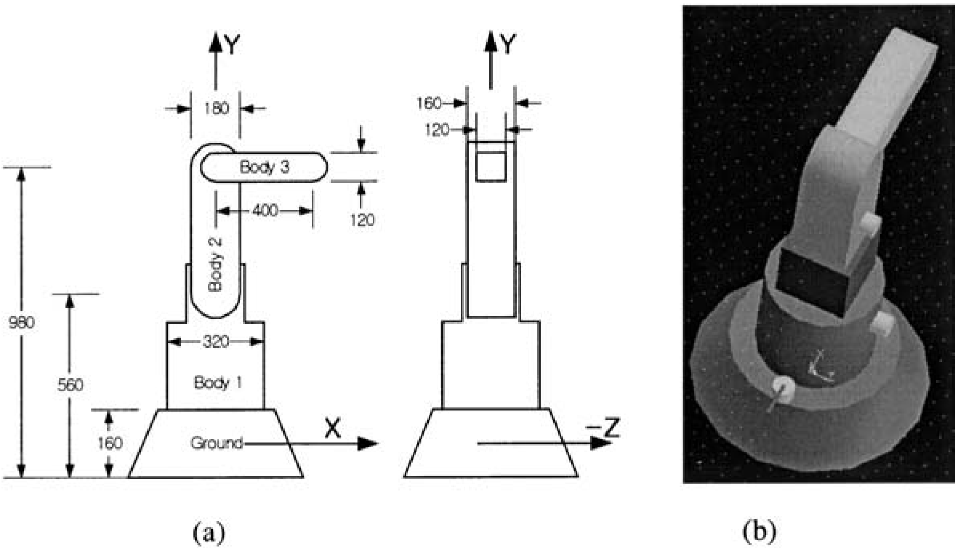

Fig. 1. The robot manipulator model: (a) the schematic diagram (b) a snapshot from animation.

where $(*)_{diag\_m}$ is a diagonal matrix including $*$ as an element and $(V_t)_{vec} = [V_{t1}, \ldots, V_{tnp}]$.

The state variables of the entire system including the electrical variables are defined as $q_{tot} = [q^T \quad \bar{q}^T]$. When $\dot{q}_{tot} \equiv v_{tot}$ and $\ddot{q}_{tot} \equiv a_{tot}$, the differential algebraic equations including the electromechanical coupling effects are

$$H_{tot}(p_{tot\_n}) = \begin{bmatrix} F_{tot}(q_{tot\_n}, v_{tot\_n}, a_{tot\_n}, \lambda_n, t_n) \\ \Phi(q_n, t_n) \\ \dot{\Phi}(q_n, v_n, t_n) \\ \ddot{\Phi}(q_n, v_n, a_n, t) \\ U_{tot\_0}^T(q_{tot\_n} + \beta_0 v_{tot\_n} + \beta_1) \\ U_{tot\_0}^T(v_{tot\_n} + \beta_0 a_{tot\_n} + \beta_2) \end{bmatrix} = 0 \quad (21)$$

where

$$p_{tot\_n} = [q_{tot\_n}^T, v_{tot\_n}^T, a_{tot\_n}^T, \lambda_n^T] \quad (22)$$

and U_{tot_0} is a $R^{nr+np} \times R^{(nr+np-nm)}$ matrix that makes the augmented square matrix $[{}^{U_{tot\_0}^T}_{\Phi_q}]$ nonsingular.

5. SIMULATION

In this section, the proposed dynamics analysis method is applied to the simulation of an industrial robot model and a model of a flexible antenna used in artificial satellites. The simulation results demonstrate the excellent performance of the proposed approach.

A 3-axis robot manipulator is modeled as shown in Fig. 1; the specifications of this robot model are given in Table I. Each of the bodies that make up the robot is constrained by revolute joints at which the driving force of the DC motor operates, and a gear model with a ratio of 199:1 is used for realistic motion of the robot.

When the motor model is not explicitly included, the driving torque is specified directly by the user as an input of the system model. In the present work, the user-specified input torques were arbitrarily assigned the step patterns. In this simulation, the reference values of the applied torques on axes 1, 2 and 3 are 500, 500, and 100 *Nmm*, respectively.

Table I. Modeling parameters of the robot manipulator.

	Size(H×W×D) (mm)	Mass (kg)	Reference axis of the body rotation
Body 1	400 × 320 × 320 (cylinder)	20	− Y axis
Body 2	420 × 180 × 160	12	Z axis
Body 3	400 × 120 × 120	8	Z axis

When a DC motor is included in the robot model, the input variable is not torque but voltage. In this case, the driving torque of the motor is determined by the ODEs governing the motor dynamics, which are affected by the motion of the robot. To generate the desired torque, the input voltage should be properly determined, but in practice this is difficult. This problem can be solved by using a motor driver/controller, a device that makes the relation between input voltage and driving torque easy for users to understand. However, the torque generated by the input voltage may differ from the desired torque, depending on the state of the mechanical components connected to the motor as well as on the characteristics of the driver/controller. This difference can be identified in the results of simulations of the dynamic behavior of the robot including the motor and driver models, which are described below.

Before the driver model can be applied, the motor model must first be specified. The motor model is completed by applying parameters measured in experiments on a real motor to the motor dynamics equation, as described in Section 3. In the present simulations, the parameters of the driving motor were taken as those of a brushless DC motor of the Parker Hannifin Corporation (model name: BE343J). Table II shows the vendor-supplied information on the parameters of this motor.[15] The driver model applied is shown in Fig. 4; in the

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Table II. DC motor parameters (Parker Hannifin Corporation, BE343J).

Parameter	Units	Value
Peak Current	Amps Peak	32.2
Voltage Constant	Volts/rad/s	0.468
Torque Constant	Nm/Amp Peak	0.402
Resistance	Ohms	0.96
Inductance	MH	15.09
Viscous Damping	Nm/Krpm	1.2×10^{-2}
Static Friction	Nm	2.9×10^{-2}
Maximum Bus Voltage	Volts DC	340
Rotor Inertia	$Kg \cdot m^2$	7.1×10^{-5}
Motor Weight	Kg	4.3

ideal case, the input voltage is proportional to the generated torque.

Now consider the circuit shown in Fig. 2. Let R_m be the load occurring at the motor and i_1 be the feedback current. As shown in Fig. 2, we assume that $i_1 = 0$. Then, the relation between the current flowing into the motor current, i_m, and the input voltage, V_{in}, can be expressed as follows:[16]

$$i_m = \frac{V_{in}}{R_1 + R_m} \times \frac{1}{[1/A + R_1/(R_1 + R_m)]} \tag{23}$$

where A is the gain of the driver. If $A \gg (1 + R_m/R_1)$, then

$$i_m \approx V_{in}/R_1 \tag{24}$$

that is, the current flowing into the motor current, i_m, can be assumed to be proportional to the input voltage, V_{in}. To generate the same values of the reference torques, the input voltage V_{in} is determined by Eq. (15) and the assumption $A \gg (1 + R_m/R_1)$.

When $A = 100$, $R_1 = 10$ and the determined voltage V_{in} is inputted into the robot model including the driver/controller and motor models, the torque generated at each joint of the robot is as shown in Fig. 3. The magnitudes of the initial torques are similar to the reference torque input specified, except that the magnitudes of the torques decrease instead of remaining constant. This decrease in the torques arises because the current drift caused by the increase in the backward electromotive force cannot be curbed, not even by the voltage compensation of the driver circuits. In addition, the positive step exceeds the reference level 500 *Nmm*; this result is caused by nonlinear effect of the motor driver. A sudden increase of the motor current can raise the driver nonlinearity and make Eq. (24) invalid. This procedure is applied to clarify the comparison between the reference torque and the generated torque. In real systems in which the motor and its H-bridge driving circuits are included, the values of generated torque can be different from the desired values of torque as explained.[17]

The position trajectories of the end of the robot arm obtained from the two simulation models are shown in Fig. 4. It is clear from Fig. 4 that the two simulation models give substantially different motions of the robot. Since the real robot system uses a motor to generate the applied torques, the simulation results from the model that explicitly includes the motors should be much closer to the actual response of the robot system. In cases where the required torque and power are within the capacity of the motor driver/controller, the simulation results from the two models may not be very different. Therefore, the performance of the robot system can be guaranteed only in certain cases if its controller

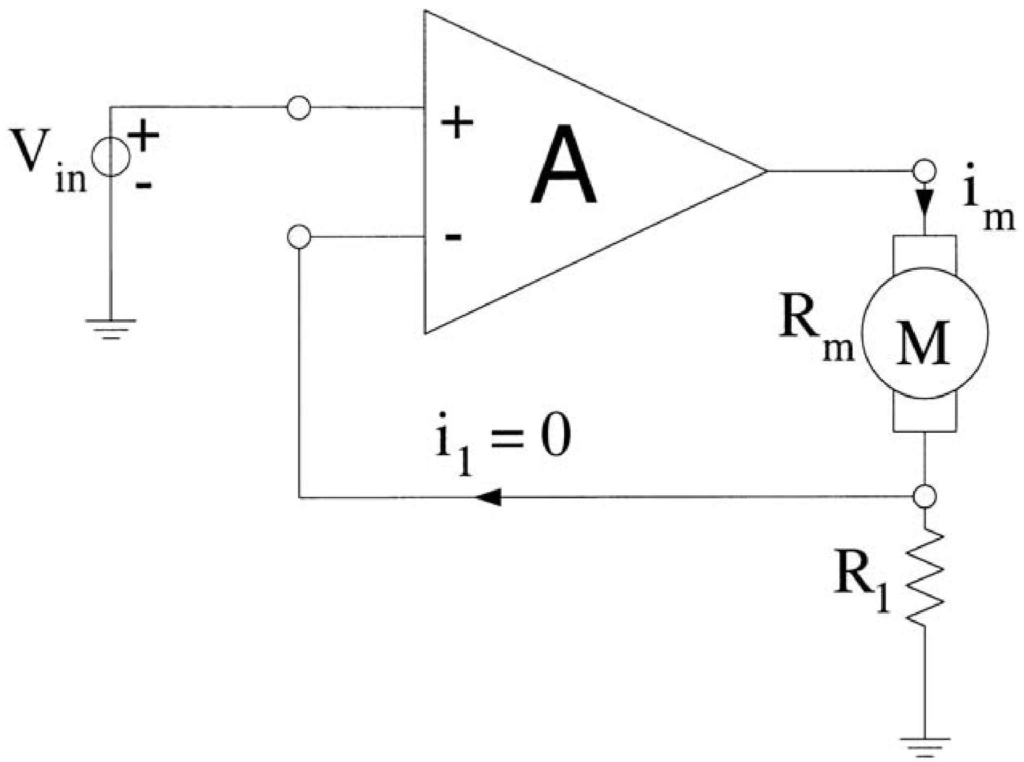

Fig. 2. A simple model of a DC motor driver.

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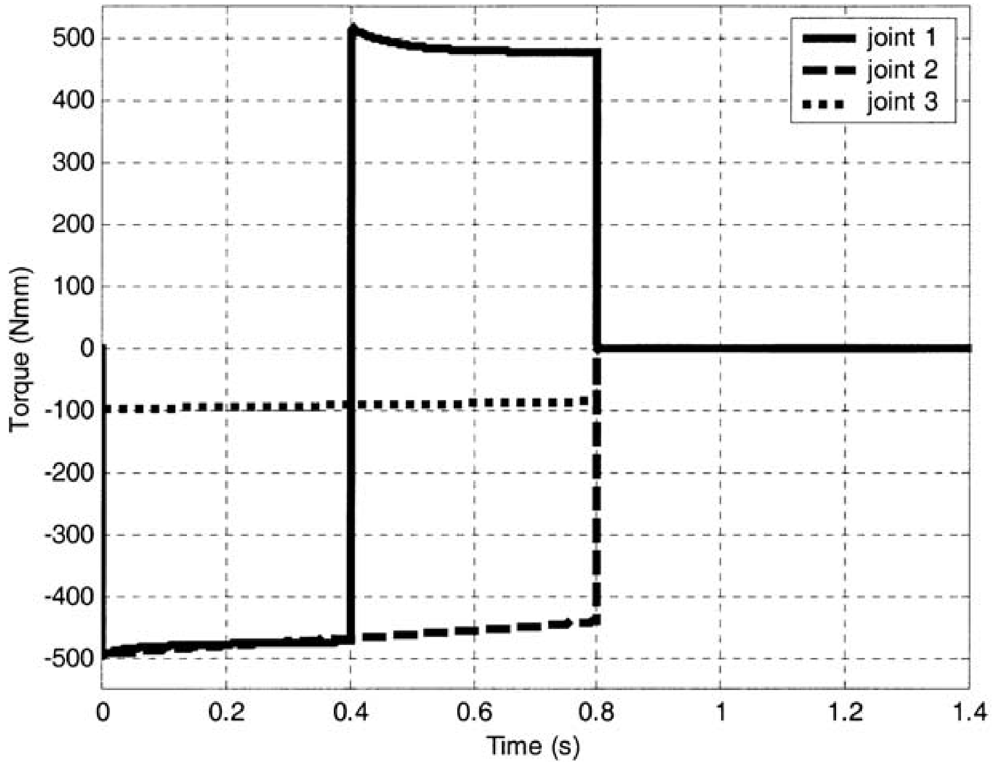

Fig. 3. Torque generated by driver/motor model.

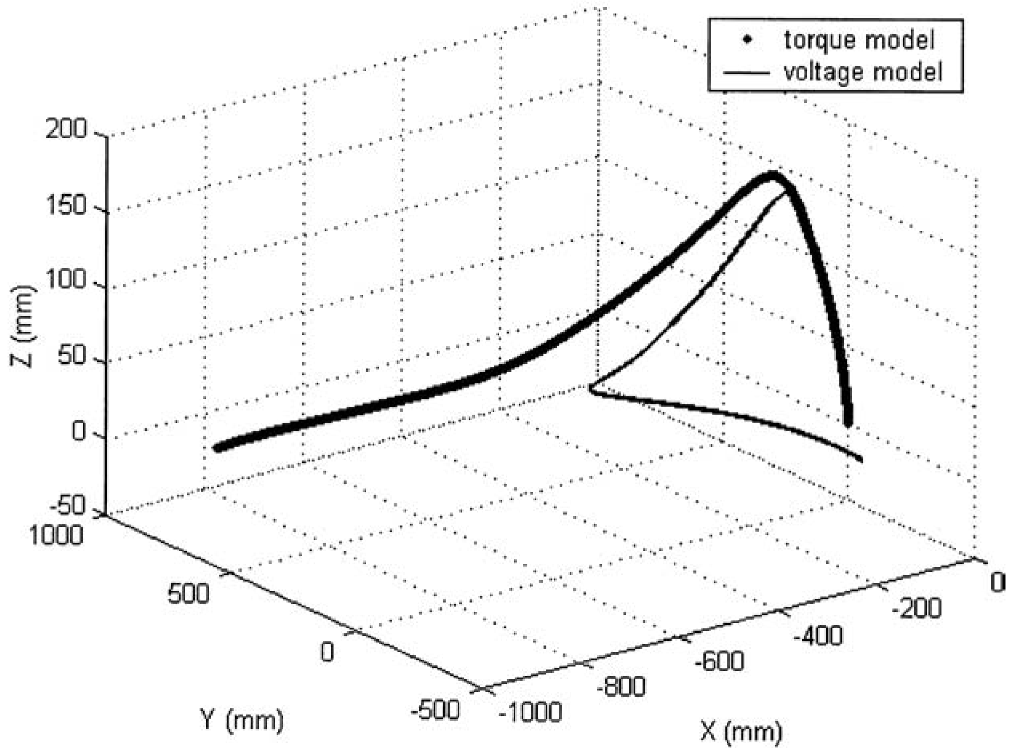

Fig. 4. Trajectories of position of the end-effecter of robot.

is designed using the system model that does not include the dynamic characteristics of the motor. However, if the system model including the motor dynamics is used in the design of the system controller, the system will perform well under a greater range of operating conditions because the plant model of the control system will be more realistic and reliable.

One reason for the past neglect of DC motor dynamics in dynamic simulations of mechanical systems is that the response time of the electrical system is usually much shorter

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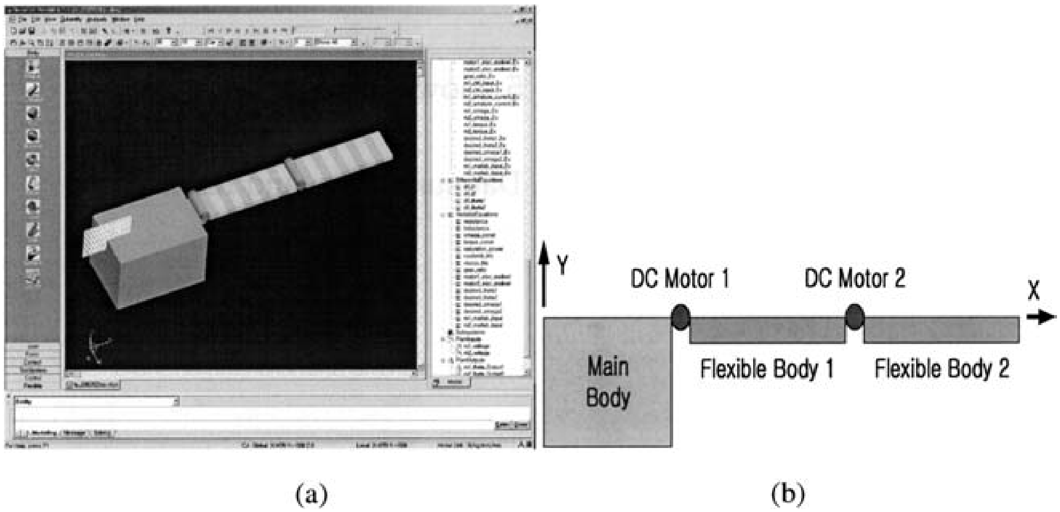

Fig. 5. Ru satellite model with flexible antennae: (a) snapshot from animation (b) schematic diagram.

than that of the mechanical system. However, the example presented here shows that the dynamic characteristics of a DC motor cannot be neglected even under very simple operating conditions.

We now consider the modeling of the antenna of an artificial satellite, shown in Fig. 5. Such antennae are hard to control and sensitive to external forces because they are composed of long flexible bodies.[18,19] The antenna considered here provides a good system for demonstrating the benefits of explicitly including the motor dynamics in the simulation program because tiny motions of the antenna structure can degrade the antenna's reception of electromagnetic waves.

The satellite antenna considered here is made up of two flexible bodies attached to the main body of the satellite, with DC motors operating on the joints between the bodies (see Fig. 5). The two bodies that make up the antenna, named Flexible Body 1 and Flexible Body 2 in Fig. 5, each have dimensions of 1840(L) × 640(W) × 100(D) mm, a mass of 25 kg, and a natural frequency of 4 Hz. The model of each flexible body in the antenna system is constructed from 9 massless beam elements and 10 lumped mass elements in the multi-body dynamics simulation package in order to enable bending motion of the antenna. A gear ratio of 100:1 is used and zero gravity is assumed. The bearing friction of the DC motors is neglected so as not to complicate the results of the dynamic simulations. The motor data used in the simulation of the robot model, described above, are also used in the antenna simulation.

In order to observe the dynamic behavior of the antenna system, a sinusoidal voltage of form $V_{in} = 15\cos(\pi t)$ is arbitrarily chosen as the input voltage for Motor 2 and the joint at which Motor 1 is installed is set to be fixed at the main body so that the effect of Motor 1 is decoupled from that of Motor 2 in the simulation. The periodic input voltage brings about periodic torques at the joint where the motor is installed, which should result in periodic motion of the antenna body. However, the variation in the velocity of the antenna bodies causes backward electromotive forces in the motors, and the resulting variation in the frequency of the input voltage may disrupt the periodic nature of the mechanical responses of the antenna structures. Fig. 6 shows the userspecified torques for the system model without the motor model and the torques generated by the motor obtained from simulations using the system model that includes the motor dynamics. The generated torque is similar to the user-specified torque except at short times. The angular velocities of Flexible Body 2 obtained from the simulations are shown in Fig. 7. Since a large initial jump in the voltage input is required to precisely achieve the desired torques (the dotted line in Fig. 6) in simulations using the system model that includes the dynamics of the motors, the torque generated by the motor cannot precisely track the desired value due to inertial effects in the motors and drivers/controllers. This behavior, shown in Fig. 6, more closely resembles the torque time history in real systems than does the user-specified torque behavior in simulations that do not explicitly include the motor dynamics. As can be seen in Fig. 7, the angular velocities from the system model with the motors are very different from those obtained from the model without motors, even though the curves have similar shapes.

6. CONCLUSION

A method for simulating multi-body robotic systems driven by DC motors has been developed. The numerical analysis program was constructed by embedding the equations of a DC motor model into the algorithm for the simulation of multi-body dynamics, which was previously developed by the authors. The dynamic behaviors of the robotic systems driven by motors are successfully simulated using the developed numerical analysis package. On observing the responses of the robotic systems driven by motors, it is found that the electromechanical coupling effects inside the DC motor have an influence on the dynamics of the entire system. The inclusion of this coupling effect enables more realistic and reliable prediction of the dynamic responses of robotic systems with multiple bodies driven by motors. Two mechanical systems containing DC motors – an industrial robot system and a flexible satellite antenna – were

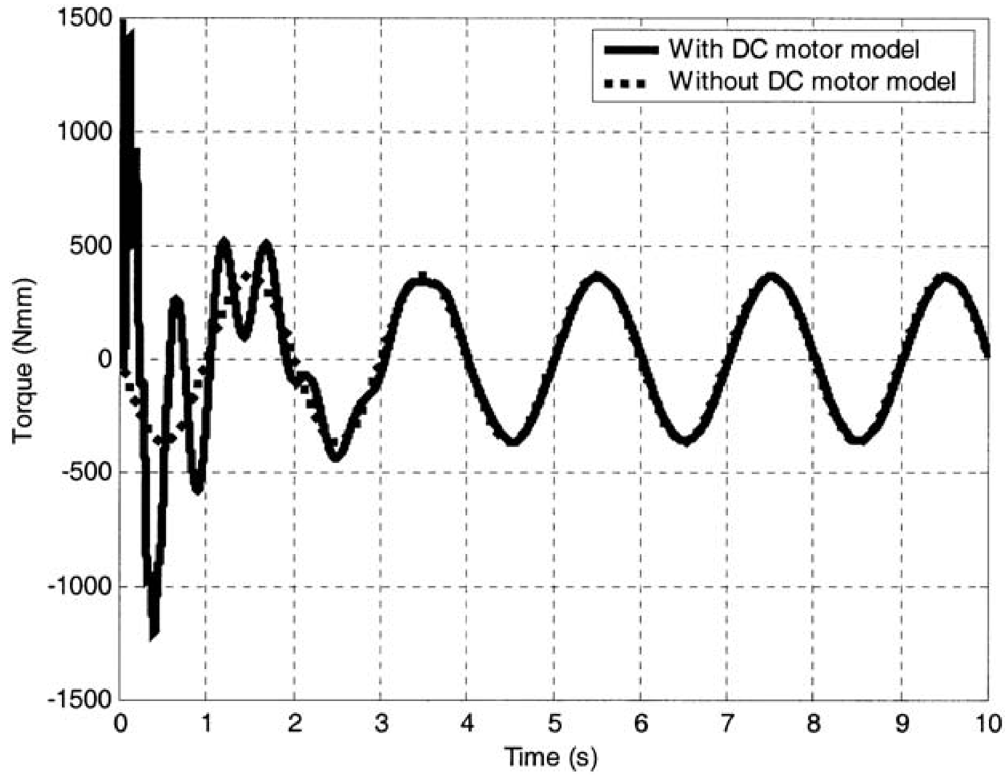

Fig. 6. The desired input torque and the generated torque.

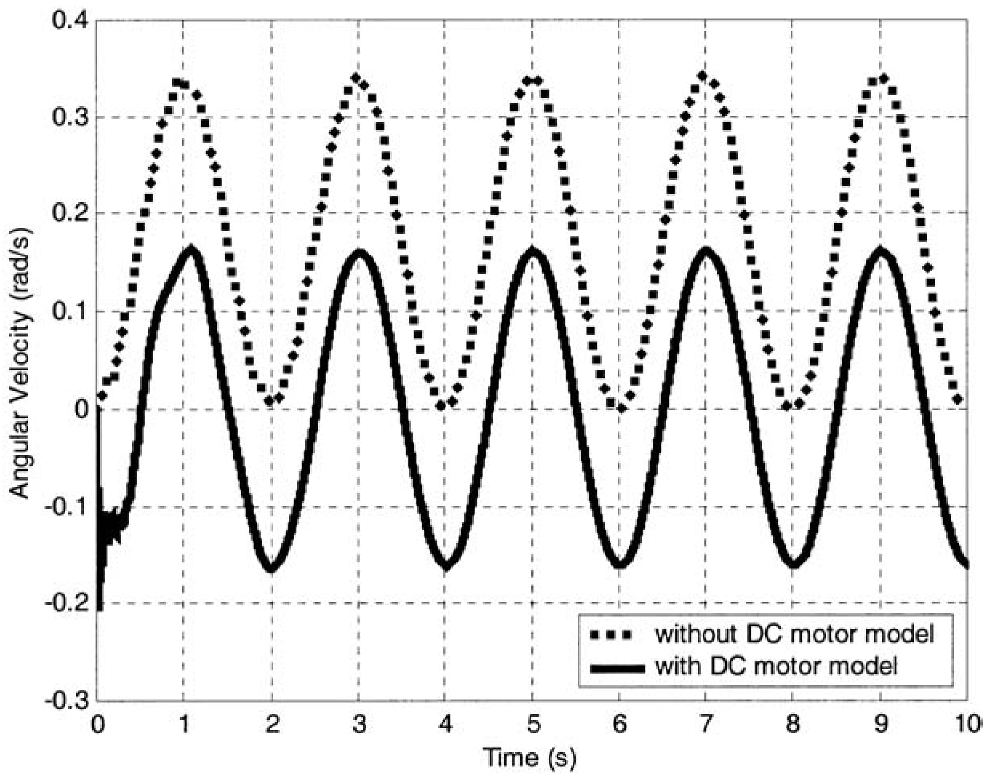

Fig. 7. The angular velocity of Flexible Body 2.

considered to test the developed numerical analysis package. In the simulation results for the robot manipulator, it was shown that the torque generated by the input voltage of the DC motor model can be considerably different from the desired torque. In the results of simulations of a flexible antenna system for a satellite, it was found that simulations ignoring the electromechanical coupling effects inside the DC motors may provide unrealistic predictions of the transient responses of the system, and that even in a steady state the results of such simulations may be dubious because the amplitude of the steady response varies with the frequency of the input voltage. Therefore, the developed simulation package for dynamic responses of multi-body system including motors is useful in designing various kinds of robotic systems driven by motors, especially in designing the system controllers and driving circuits.

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