Vibration Control of Truck Crane by Variable Constrained Control with Neural Network

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This paper is concerned with vibration control for motion of a truck crane by using multi-body dynamics (MBD) theory. Truck cranes are used for loading, mounting and carrying loads. It is desired to control motions of the truck crane for efficiency and safety under operations. Then the swinging motion of the suspended load occurs during working motion and also after the work is completed. It is important to reduce the vibration because of working efficiency and safety. This paper deals with derricking motions of the crane boom. The dynamic characteristics of the truck crane changes during derricking motions. The MBD theory represents behavior of machinery by differential algebraic equations (DAEs). As the derricking motions of truck cranes have nonlinear characteristics dependent on boom angles, it is convenient to simulate truck crane motions by the MBD theory.

On the other hand, many researchers have considered approaches to control the MDB systems. One of control procedures for MDB system is the variable constrained control (VCC) method. The VCC method can solve the inverse dynamics of MBD system via DAE and determine the control forces to follow desired motion patterns. However, the positioning and swing control of a suspended load should be simultaneously performed by only elevating motion of the crane boom. Then the crane system is regarded as an under-actuated system. It is difficult to achieve the two objects by a control input. Therefore, a procedure is proposed to combine VCC with gain schedule (GS)-PD control. The control gains of the PD control are tuned by using the neural network (NN). The VCC with GS-PD control which has variable gains adjusted by the NN are applied to the crane system to accomplish the both objects.

The validity of the combined procedure of VCC and GS-PD control is verified by numerical calculations. The learning of the weighted coefficients of NN is completed after several computations. The positioning and swing control of the load are realized by the proposed procedure. First the crane boom is elevated from 20° to 60° with constant wire rope length. Next the control procedure is applied to the horizontal transfer of the suspended load and the case with initial swing of the load in elevating motion. Then, the controller is applied to an experimental crane model. The similar operations to the numerical calculations are carried out. The sufficient performance for vibration suppression and positioning is verified in the experiments. The results demonstrate the effectiveness of the VCC and GS-PD control for the various elevating operations of truck crane.

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ABSTRACT

This paper is concerned with vibration control for elevating motions of a truck crane by using multi-body dynamics (MBD) theory. The MBD theory represents behavior of machinery by differential algebraic equations (DAEs). The variable constrained control (VCC) has been applied to the MBD systems. When the positioning and swing control of a suspended load are simultaneously performed by only elevating motion of the crane boom, the crane is regarded as an under-actuated system. VCC and PD control which has variable gains adjusted by neural network (NN) are combined to accomplish the both objects. Validity of the novel combined procedure of VCC and PD with variable gains is verified by numerical calculations. The proposed controller is definitely applied to an experimental crane model.

1. INTRODUCTION

Truck cranes are used for loading, mounting and carrying large loads. Then the swing motion of the payload occurs during working motion and also after the work is completed. It is important to reduce the vibration because of working efficiency and safety. The swing control has been researched by many workers, Klosinski (2005) and Terashima (2007), etc. The dynamics of truck cranes is affected by their boom position and payloads. It is necessary to develop a control procedure to adapt for various operating conditions. The gain scheduled control method, Takagi (2003), is employed for vibration suppression of the tower crane. Recently, the multi-body dynamics (MBD) theory, Haug (1989) and Tohyama (1993), have been employed for the kinematic analysis of mechanical systems. Various type of formulation for MBD theory has been developed, Tajima (1997, 2007). The flexible MBD theory, Nanjo (2008), has been also applied to construction machinery such as excavators and cranes. In addition, it is one of the most important issues to combine MBD theory with motion and vibration control. The variable constrained control (VCC) method is proposed to control systems such as a under water vehicle, Ikeda (2001),

and a hopping robot, Ikeda (2003), which have nonholonomic constraints. The control forces constrains motions of the system.

This paper deals with elevating motions of the crane boom. The VCC method is applied to truck crane and to control positioning and swing suppression simultaneously. It is difficult to accomplish the both purposes by only using the VCC, because the sway angles between boom and wire rope can not be directly control. Then, a gain scheduled PD (GS-PD) control is secondarily used to overcome the problem, which has variable gains adjusted by neural network (NN), Fujinaka (2006). Validity of the combined procedure of VCC and GS-PD control is verified by numerical calculations. Finally, the proposed controller is applied to an experimental crane model.

2. CRANE MODEL

A simplified crane model considered for elevating motion shown in Figure 1 is formulated by using differential algebraic equations (DAEs). The equation of motion with constraints is written as

$$M(q)\ddot{q} + h(q, \dot{q}) = \Phi_q^T(q)\lambda \quad (1)$$

Figure 1 CRANE MODEL.

where q denotes generalized coordinate which consists of (x_1, y_1, θ_1) , (x_2, y_2, θ_2) , (x_3, y_3, θ_3) of body 1, 2, 3. The boom elevating angle and the swing angle of wire rope are represented as $\theta_2 = \theta$ and $\theta_3 = \phi$. M , h , Φ and λ are respectively a mass matrix, damping and restoring forces term, constraint equations and Lagrange's multipliers. Φ_q denotes derivative of Φ by the subscript q . The mass matrix represents

$$M = \text{diag}[m_1, m_1, I_1, m_2, m_2, I_2, m_3, m_3, I_3] \quad (2)$$

where $\text{diag}[\cdot]$ denotes diagonal matrix. m_1 , m_2 , m_3 and I_1 , I_2 , I_3 show mass and moment of inertia of body 1, 2 and 3. These bodies are sequentially combined with rotational constraints. Then, the constrained equations are obtained as

$$\Phi = \begin{Bmatrix} x_1 - \frac{l_1}{2} \cos \theta_1 \\ y_1 - \frac{l_1}{2} \sin \theta_1 \\ \theta_1 - \frac{\pi}{2} \\ x_2 - \frac{l_2}{2} \cos \theta_2 - x_1 - \frac{l_1}{2} \cos \theta_1 \\ y_2 - \frac{l_2}{2} \sin \theta_2 - y_1 - \frac{l_1}{2} \sin \theta_1 \\ x_3 - \frac{l_3}{2} \cos \theta_3 - x_2 - \frac{l_2}{2} \cos \theta_2 \\ y_3 - \frac{l_3}{2} \sin \theta_3 - y_2 - \frac{l_2}{2} \sin \theta_2 \end{Bmatrix} = \{0\} \quad (3)$$

where l_1 , l_2 , l_3 are length of bodies 1, 2, 3, respectively. The dynamic characteristics of the constrained equations is described as

$$\ddot{\Phi}(q) + C \dot{\Phi}(q) + K \Phi(q) = 0 \quad (4)$$

where C and K are coefficients related to velocity and displacement. The following DAEs are derived from Eqs.(1), (3) and (4).

$$\begin{bmatrix} M & -\Phi(q)_q^T \\ -\Phi(q)_q & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \end{Bmatrix} = \begin{Bmatrix} -h(\dot{q}, q) \\ \ddot{\Phi}(q) + C \dot{\Phi}(q) + K \Phi(q) \end{Bmatrix} \quad (5)$$

3. CONTROL PROCEDURE

3.1 Variable Constrained Control (VCC)

The VCC provides the required control forces to the corresponding joints in order to operate in desired motions. The equation of motion (1) and the control forces are considered by the following formula.

$$M(q)\ddot{q} + h(q, \dot{q}) = \Phi_q^T(q)\lambda + f_q^T(q)u \quad (6)$$

where $f(q)$ is a direction vector of control forces, $f_q^T = \partial f / \partial q$ denotes the Jacobian matrix. The desired motion is assumed to be

$$\xi(t) = g(q(t)) \quad (7)$$

The differentiation of eq.(7) with respect to time is derived to

$$\dot{\xi}(t) = g_q \dot{q}(t) \quad (8)$$

and once more differentiation is performed.

$$\ddot{\xi}(t) = g_q \ddot{q}(t) + \dot{g}_q(t) \dot{q}(t) \quad (9)$$

The control forces and the control constraints are gathered with the DAEs (5).

$$\begin{bmatrix} M & -\Phi(q)_q^T & -f_q^T(q) \\ -\Phi(q)_q & 0 & 0 \\ -g_q & 0 & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \\ u \end{Bmatrix} = \begin{Bmatrix} -h(\dot{q}, q) \\ \ddot{\Phi}(q) + C \dot{\Phi}(q) + K \Phi(q) \\ \dot{g}_q \dot{q}(t) - \ddot{\xi}(t) \end{Bmatrix} \quad (10)$$

Even if $\ddot{\xi}(t)$ is not explicitly defined, it may be described as $\ddot{\xi}(t) = \eta(\xi(t), \dot{\xi}(t), t)$. The inverse dynamics which obtain the control forces yielded from the desired motions is solved by using Eq.(10). The control forces constrain the control object to tracking the desired motions. However, it is difficult to realize two objects of swing control of a

Figure 2 NEURAL CONTROL SYSTEM FOR TRUCK CRANE.

suspended load and boom positioning by only a joint motion at boom root. Therefore, a complementary procedure must be combined to the VCC. The VCC deals with nonlinear characteristics for gravity effects which depend on the boom elevating angle, and the PD controller complements accomplishment of the control objects. Since the complementary control also must consider the variation of dynamics, the control gains are adjusted with boom elevating angles and swing angles. The gain scheduling are carried out by neural networks (NN) where the weighted coefficients are learned by measured data of the boom elevating angles and the swing angles of the load.

3.2 Gain Scheduled PD (GS-PD) Control

The control procedure is proposed to implement swing control and boom positioning. The diagram of the control flow is presented in Fig.2. The complementary PD controller is used with VCC. Here, r is a target of swing control and r' is a target of positioning. y denotes state values of the crane. The present state values and the target values enter the VCC controller to derive the control forces at the next step from inverse dynamics. The deviation e between the target values and current state values can be obtained. The complementary control forces for the deviation e are calculated by the GS-PD controller. The crane dynamics is dependent on boom elevating angle and weight of a suspended load. The control gains should be adapted to variation of the dynamics by a gain scheduled controller. The PD gains are scheduled by using a hierarchical Neural Network shown in Fig.3. The inputs of NN are state variables and control forces of the crane and the outputs are PD gains. W_{ji} and W_{kj} are weighted coefficients and $u(n)$ and $y(n)$ denote control forces and state variables at n th sampling time. K_p and K_d are respectively the proportional gain and the differential one for swing control. K'_p and K'_d similarly denote positioning gains.

3.3 Learning Algorithm

The NN learning algorithm to obtain the GS-PD control gains are shown as follows;

Step 1: Initialization

Set NN parameters; the number of neurons in layers i , j and k , the weighted coefficients W_{ji} and W_{kj} , the update factor, η , for weighted coefficients, inertia term, β , threshold value, σ , and tolerance of learning convergence, ε .

Step 2: Inputs of NN

Input the PD control forces $u(n)$ for swing control and positioning and the state variables $y(n)$; $[\theta, \dot{\theta}, \phi, \dot{\phi}]$ of the crane to NN.

Figure 3 HIERARCHICAL TYPE NEURAL NETWORK.

Step 3: Calculate outputs of NN

$$O_j = f(\text{net}_j), \quad \text{net}_j = \sum_{i=0}^M W_{ji} O_i - \sigma_j \quad (i = 1, 2, \dots, M, \quad j = 1, 2, \dots, N) \quad (11)$$

$$f(x) = 1/(1 + \exp(-x)) \quad (\text{sigmoid function})$$

$$O_k = f(\text{net}_k), \quad \text{net}_k = \sum_{j=0}^N W_{kj} O_j \quad (k = 1, 2, 3, 4) \quad (12)$$

Step 4: Compensate control forces

$$\bar{u} = K_p (r(n) - \phi(n)) + K_d (\dot{r}(n) - \dot{\phi}(n)) + K'_p (r'(n) - \theta(n)) + K'_d (\dot{r}'(n) - \dot{\theta}(n)) \quad (13)$$

where the target angles $r(n)$ and velocities $\dot{r}(n)$ of swing control are set to zero. The targets $r'(n)$ and $\dot{r}'(n)$ of positioning are provided by the desired motion. The complementary control forces $\bar{u}(n)$ are appended to the control forces $u(n)$ from VCC.

Step 5: Calculate generalized errors

$$\delta_k = e_k(n+1) J(n) \frac{\partial \bar{u}(n)}{\partial O_k} \quad (14)$$

$$\text{where } J(n) = \sum_{j=1}^N W_{kj} O_j (1 - O_j)$$

$$\delta_j = \sum_{k=1}^4 \delta_k W_{kj} O_j (1 - O_j) \quad (15)$$

Step 6: Update weighted coefficients

$$W_{ji}(n+1) = W_{ji}(n) + \eta \delta_j O_i + \beta \Delta W_{ji}(n) \quad (16)$$

$$\text{where } \Delta W_{ji}(n) = W_{ji}(n) - W_{ji}(n-1)$$

$$W_{kj}(n+1) = W_{kj}(n) + \eta \delta_k O_j + \beta \Delta W_{kj}(n) \quad (17)$$

$$\text{where } \Delta W_{kj}(n) = W_{kj}(n) - W_{kj}(n-1)$$

Step 7: Determine convergence

Iterate from Step 2 to Step 6. Decide continuation of learning at the end of simulation.

$$\text{If } \sum_{k=1}^4 E_k(n+1) \leq \varepsilon$$

$$\text{where } E_k(n+1) = \frac{1}{2} e_k(n+1)^2,$$

$$\varepsilon \text{ is tolerance} \quad (18)$$

then Stop Learning

else Continue Learning

Restart simulation with the preserved NN weighted coefficients.

4. NUMERICAL CALCULATION

4.1 Simulation Parameters

The following crane parameters are used in numerical calculations. These parameters are determined from an experimental model in our laboratory. The crane model has the boom length, 0.8m, the wire rope length, 0.6m and the weight of suspended load, 0.3kg, in brief outline. The parameters of each body used for DAEs are chosen as follows; Base (Body 1): $m_1 = 0.6\text{kg}$, $I_1 = 0.083\text{m}^2$, $I_1 = 1.81 \times 10^{-3}\text{kg} \cdot \text{m}^2$, Boom (Body 2): $m_2 = 0.19\text{kg}$, $I_2 = 0.8\text{m}$, $I_2 = 1.01 \times 10^{-2}\text{kg} \cdot \text{m}^2$. Suspended load and wire rope (Body 3): $m_3 = 0.3\text{kg}$, and the moment of inertia is dependent on wire rope length. Therefore, the moment of inertia is $I_3 = 4.43 \times 10^{-4}\text{kg} \cdot \text{m}^2$ for the wire rope length $l_3 = 0.6\text{m}$. The moment of inertia is recalculated as the wire rope length changes at each time.

The numerical calculations are performed by the semi-implicit Runge Kutta method, Fujikawa (2003). The time step of the numerical integration is 0.01sec. The desired acceleration pattern is defined by the sinusoidal function.

$$\ddot{\xi}(t) = A \sin(\omega t), \quad (\omega = 2\pi/T) \quad (19)$$

where the operating time is $T = 4\text{sec}$. A is the acceleration amplitude to move the boom from the initial position to the target angle. The boom elevating angle is operated from 20° to 60° . The acceleration pattern of

elevating angle is shown in Fig.4.

The three controllers are applied to the crane model.

Method A: Boom positioning (No swing control)

Method B: Positioning and swing control
(Constant gains)

Method C: Positioning and swing control
(Gain scheduled)

4.2 Calculation Results

Fig.5 shows the swing angles of wire rope. The wire rope has constant length of 0.6m, and the boom was elevated from 20° to 60° . The sway motions of the suspended load are suppressed after 4.5s in Methods B and C, whereas the vibration remains in Method A. Though the difference of amplitudes between Method B and C is not significant, Method C decreased the residual vibration slightly faster than Method B. It was possible that the PD controller with the fixed gains dealt with the operation. The PD gains were decided as $K_p = 0.4$, $K_d = 0.2$, $K'_p = 0.4$ and $K'_d = 0.3$. The satisfied results can be obtained by the fixed gains which are individually adjusted to various operations. However it is disadvantageous to require the adjustment of gains to every operation. The GS-PD controller is convenient for decision of the gains.

Fig.6 shows the swing angles in horizontal translation of the suspended load to elevate the boom and lengthen the wire rope. Then the boom was elevated from 20° to 60° similarly to the previous example. The residual vibration remains after the translational operation and the amplitude of swing angle do not quite decrease in Method A. Although the residual vibration of Method B can be reduced, the amplitudes in the vicinity of 4sec are larger than those of Method A and the residual vibration does not completely converge in 15sec. The fixed-PD gains were

Figure 4 ACCELERATION OF BOOM ELEVATING
ANGLE.

Figure 5 SWING ANGLE OF WIRE ROPE (SIMULATION).

Figure 7 SWING ANGLE OF WIRE ROPE (EXPERIMENT).

Figure 6 SWING ANGLE OF WIRE ROPE IN
HORIZONTAL TRANSFER (SIMULATION).

Figure 8 ELEVATING ANGLE OF BOOM (EXPERIMENT).

decided as $K_p = 0.3$, $K_d = 0.2$, $K'_p = 0.5$ and $K'_d = 0.3$. The amplitudes during the elevating motion are suppressed in Method A. The residual vibration converged rapidly. The Method C was adjusted to variation of the dynamics caused by the rope lengthened.

5. EXPERIMENT

5.1 Experimental Apparatus

The parameters of the experimental apparatus are similar to ones used in the previous simulations. The three controllers, Method A, Method B and Method C, are also applied to an experimental crane model in the same way as the simulations. Although the motor torque was used as the control variable in the simulations, the angular velocities of

elevating motor are employed for convenience. We choose the initial weighted coefficients of NN which derived to effective results in the simulations.

5.2 Experimental Results

First, the sway angles of wire rope are shown in Fig.7, when the boom was elevated from 20° to 60° with fixed wire rope length as $0.6m$. The experimental results are in good agreement with the numerical calculations. Method B and C probably have the equivalent ability of suppression for residual vibration, as dynamics of the crane model little change after elevating operations finish. The PD gains in Method B were set to $K_p = 0.4$, $K_d = 0.2$, $K'_p = 0.5$ and $K'_d = 0.6$. Fig.8 shows the elevating angles of the crane boom. The overshoots are

Figure 9 VARIATION OF THE CONTROL GAINS (EXPERIMENT).

Figure 11 SWING ANGLE OF WIRE ROPE WITH INITIAL SWING (EXPERIMENT).

Figure 10 SWING ANGLE OF WIRE ROPE IN HORIZONTAL TRANSFER (EXPERIMENT).

Figure 12 SWING ANGLE OF WIRE ROPE FOR OTHER LOAD WEIGHT (EXPERIMENT).

observed in Method B and C, which are caused by swing control. Method C completely converged the boom angle in 6sec and the minute variation remained in Method B. Naturally, Method A fixed the boom angle on 60° in 4sec, because the positioning was simply performed by the VCC. Method C could sufficiently accomplish two purposes at a time. Then the control gains change with time and the GS-PD controller adequately exert boom positioning and swing control. The time-variable characteristic of the proportional gains and the differential ones are represented in Fig.9. It is apparent that the gains start varying with boom elevating motions and converges to constant values after 6sec except small fluctuation. The GS-PD gains can be adapted to the crane dynamics.

Fig.10 shows the experimental results of the swing angles in horizontal translation of the suspended load. The boom was elevated from 20° to 60° and the wire rope was lengthened to keep the height of load above the ground. Although the minute vibration remains in 10sec in Method C, the swing motions can be satisfactorily suppressed. Method B was not applied to this operation or later, because the fixed PD gains in Method B had to be adjusted to every operation. The effects of the initial swing angles are described in Fig.11. Then the initial swing angles were generated by up and down motions of the boom and the transporting operation started from 10sec, where the constant wire rope length was 0.6m. The swing vibration almost converged on 16sec. Fig.12 shows

the results for different weight of the suspended load. The weight was increased from 0.3kg to 0.5kg and the wire rope length was fixed as 0.6m. The amplitudes of residual vibration in Method A become larger than ones of 0.3kg in Fig.5. However, the swing vibration in Method C is suppressed appropriately. The VCC and GS-PD control was adapted to the various operations. The effect of the proposed procedure was verified from these results.

6. CONCLUSION

The dynamics of truck cranes is affected by their boom position and payloads. The control procedure for positioning of crane boom and vibration of suspended load were proposed by using MBD theory and the GS-PD control with NN learning in elevating operation. Validity of the combined procedure of VCC and PD with variable gains was verified by various numerical calculations and experimental results.

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