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Dynamic simulation of wire rope with contact †

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Abstract

We present a dynamic simulation of a wire rope involving both contacts with a winch drum and hydraulic systems using the finite element method. Rapid winch operation often causes disorderly winding of the wire rope, which is an important quality problem. Dynamic simulation is, therefore, required for design of the hydraulic winch system on construction machinery. The wire rope is modeled using by truss elements considering large displacement motion. The contact between the wire rope and the winch drum is modeled using by variable-length truss elements and bilinear spring elements. An improved Newton method is proposed for nonlinear dynamic analysis. Simulation results show that some lever operations result in rope looseness and intense pressure fluctuation.

Keywords: Dynamic simulation; Wire rope; Contact; Winch system; Truss element; Hydraulic system

1. Introduction

In the winch operation of a tower crane, when the suspension load is wound up, the wire rope cannot stop quickly during rapid operation because of the inertia force, while the winch is able to do this. This causes looseness of the wire rope and disordered winding on the winch. If the winch winding operation is carried out in a disordered winding condition, the wire rope suffers considerable damage. Therefore, the evaluation on the dynamic behavior of the wire rope becomes an important quality matter of the design stage. The contact between the wire rope and the winch drum should be considered in order to represent the dynamic behavior of the wire rope in the winding works. Moreover, coupling analysis considering the dynamic characteristics of the hydraulic system is required since the winch drum is driven by a hydraulic system.

On the other hand, research [1, 2] on multibody dynamics enable us to predict the dynamic characteristics in detail on the design stage, and they provide an essential solution and a quantitative evaluation. We have also developed a multibody dynamics simulation code “SINDYS” for the nonlinear mechanical system including the hydraulic drive system since 1985, and have utilized it widely as the multipurpose design analysis tool [3].

In this paper, we have developed a dynamic simulation model for the wire rope on the tower crane considering both contacts with the winch drum and the dynamic characteristics of the hydraulic system using SINDYS. Dynamic simulations are carried out to clarify the major factor of the wire rope looseness that occurs with rapid winch operation.

2. Coupling analysis theory of wire rope system and hydraulic system

Fig. 1 shows a tower crane that is used for this simulation. The load is wound up through the wire rope by the hydraulic winch as shown in Fig. 2. The wire rope is modeled by the truss element considering the large rotation in space. The contact between the

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wire rope and the winch drum is modeled by using the variable-length truss element with a pulley and bilinear spring element. The hydraulic system is modeled by using the pipe element, the valve element, and so on.

2.1 Equations of motion

The equations of motion in nonlinear dynamic system can be described in general as follows:

$$\mathbf{g}_m + \mathbf{g}_c + \mathbf{g}_k = \mathbf{f} \tag{1}$$

where $\mathbf{g}_m, \mathbf{g}_c, \mathbf{g}_k, \mathbf{f}$ are the inertia force vector, the damping force vector, the elastic force vector, and the external force vector respectively. The MCK type nonlinear equations of motion are obtained by linearizing the coupling system with the hydraulic drive system and the flexible linkage system at time t_n as follows:

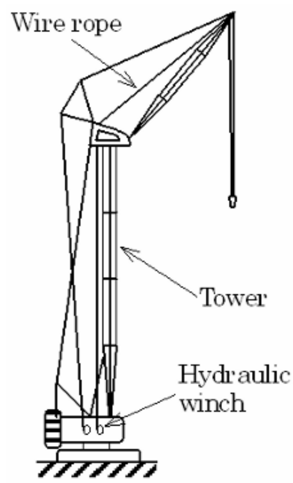

Fig. 1. Tower crane with hydraulic winch system.

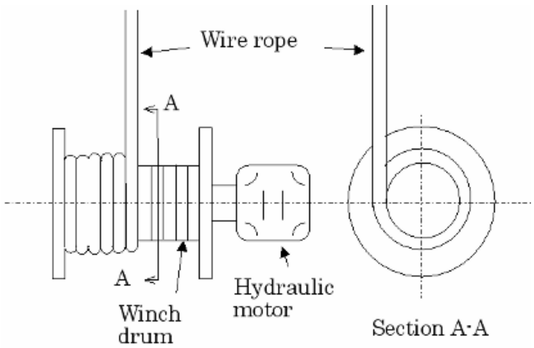

Fig. 2. Hydraulic winch system.

$$\mathbf{M}\mathbf{q}_{n+1} + \mathbf{C}\mathbf{q}_{n+1} + \mathbf{K}\mathbf{q}_{n+1} = \mathbf{f}_{n+1} - \overline{\mathbf{f}}_n \tag{2}$$

where $\mathbf{q}_{n+1}$ is the state variable vector that is the displacement vector in the flexible linkage system, and that is the integral of flow rate vector in the hydraulic system on time t_{n+1}. $\mathbf{M}, \mathbf{C}, \mathbf{K}$ are the linearized mass, damping, and stiffness matrices respectively in time t_n, $\mathbf{f}_{n+1}$ is the external force vector in time t_{n+1}. $\overline{\mathbf{f}}_n$ is the modified external force vector by linearized the non-linear element force vector in each time step.

2.2 Truss element considering large rotation

In the truss element, the motion in space and the element force can be derived from the displacement in the global frame since only the axial force arises in the element force as shown in Fig. 3. The relational expressions between the element elastic force and the node displacement can be obtained by considering the strain energy to the second order term of the displacement in order to consider geometric rigidity caused by the axial force.

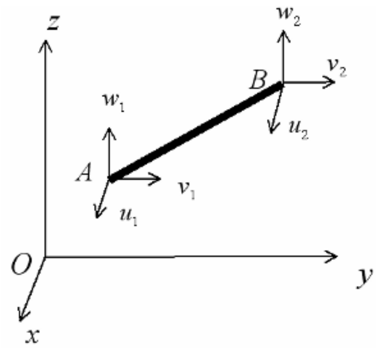

Fig. 3. Truss element in three dimensional space.

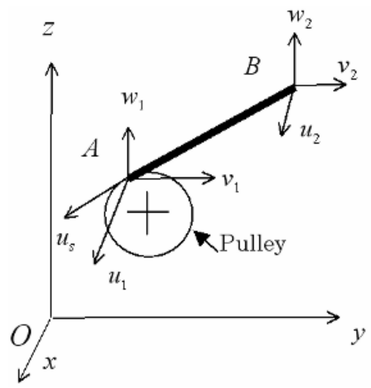

Fig. 4. Variable-length truss element.

2.3 Variable-length truss element

The variable-length truss element is an element in which the length can be changed by the rotation of a pulley as shown in Fig. 4. The relational expressions between the elastic force on the both nodal points and the displacement can be obtained by considering the strain energy to the second order term of the displacement in the same manner as the truss element.

2.4 Theory of the hydraulic drive system

The hydraulic motor element is the basic element for coupled analysis of the hydraulic drive system and the flexible linkage system. As the integrated flow rate of the hydraulic drive system and the nodal displacement of the linkage system are coupled with each other, the coupling analysis can be conducted. The valve element considering the pressure loss of the valve, the check valve for direction control, and the relief valve for pressure control are prepared for the element on the hydraulic drive system.

2.5 Computing technique for non-linear equations of motion

In the coupling analysis with the hydraulic drive system and flexible linkage system, the nonlinear characteristics are classified to two groups: one changes continuously like geometric non-linearity of the flexible linkage system and the pressure loss of the hydraulic drive system, the others have piecewise-linear characteristics such as the check valve, the relief valve, and so on. Although in the former case the Newton method is suitable for the convergence calculation by using variable time step size in proportion to the nonlinear intensity, in the latter case the Newton method is useless. A combined computing technique with the Newton method and the prediction method of the intersection point in the piecewise-linear system was proposed for the above-mentioned system.

In this technique, the initial time step-size can be set as large as possible, and the intersection point can be passed at good accuracy. In case of a high-stiffness-piecewise-linear element, the state variables come to be distorted numerically, and then the time integral characteristics should be improved by the additional mass method. The flow chart is shown in Fig. 5.

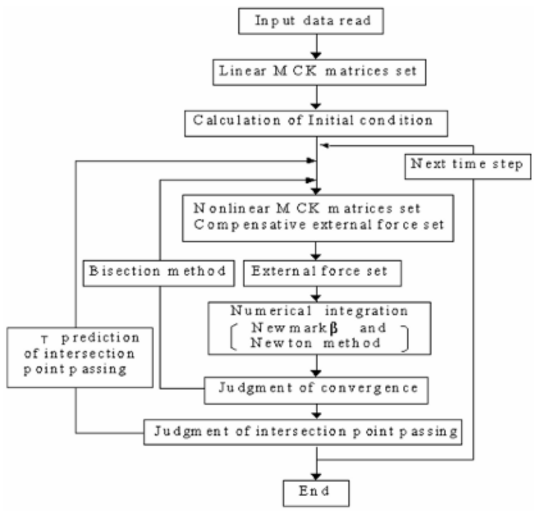

Fig. 5. Computing flow chart of nonlinear dynamic system.

3. Dynamic simulation of wire rope while rapid winch operation

3.1 The modeling of the contact between the wire rope and the winch drum

The model shown in Fig. 6 is considered in order for modeling of the contact between the wire rope and drum. The variable-length truss element is installed between each node of the truss element and the center of the winch. If the pulley of the variable-length truss element can freely rotate, the variable-length truss elements can be freely extended and shrunk, then the motion of the pulley does not affect the motion of the wire rope. The wire rope is taken up around the drum when the drum rotates in the counterclockwise direction, then the nodal point A reaches the point B. The contact spring is installed for the rotational displacement on the pulley as shown in Fig. 6(b) so that the variable-length truss element may not shorten from the condition. Therefore, the variable-length truss elements generate a large spring reaction force after the wire rope contacts the winch drum, the nodal point A will move on the winch drum after passing the point B. On the other hand, the looseness of the wire rope occurs like the point D when the drum stops rapidly. In this case, as the wire rope may move in the direction away from the winch drum, the reaction force is not generated in the contact spring. Then the contact spring may not affect the motion of the wire rope. The friction force between the winch drum and the wire rope is neglected so that looseness of the

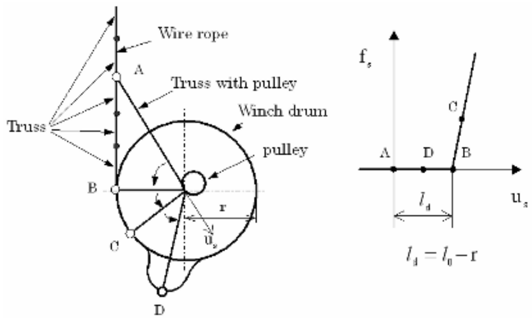

Fig. 6. Modeling of the contact between the wire rope and the winch drum.

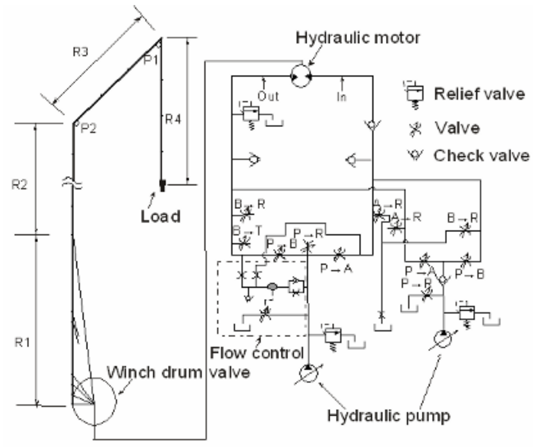

Fig. 7. Mathematical model of hydraulic winch system.

wire rope easily occurs.

3.2 Modeling of the hydraulic winch system on the tower crane

Fig. 7 shows the mathematical model of hydraulic winch system for this simulation. The wire rope is divided into the part R1 to R4. The R1 is the part taken up around the winch drum, and it is divided into 90 truss elements. In addition, the variable-length truss elements have been installed between each node and the center of winch drum, and the contact spring elements are installed at the pulley. The R4 is divided into 38 elements, and the R3 and R4 are divided into 3 and 4 elements respectively.

The hydraulic system is driven by two pumps as shown in Fig. 7. The rotational speed of the hydraulic motor, which is installed on the winch drum axis, is controlled by the opening area on the control valve according to the lever operation. The hydraulic fluid in the piping is modeled by the pipe elements considering the compressibility of the fluid.

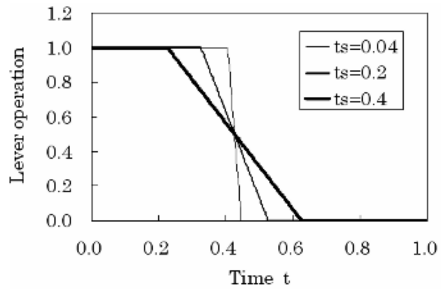

Fig. 8. Lever operation for winch system.

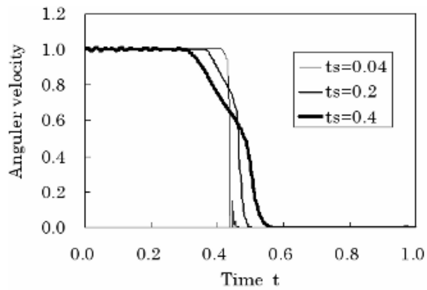

Fig. 9. Angular velocity change of the winch drum.

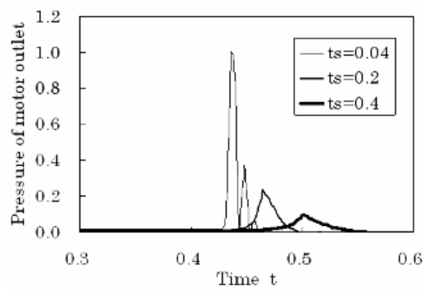

Fig. 10. Pressure change at motor outlet.

3.3 Dynamic simulation of the wire rope in the winch rapid stop

Dynamic simulations of the wire rope in the winch rapid stop were carried out using the model in Fig. 7. The load is assumed to be the no-load (only hook) so that the looseness of the wire rope is easy to arise. The initial condition is assumed to be maximum lever operation, in which the winch drum rotates at maximum rotational speed and the load is wound up. After this condition, the winch drum is made to stop according to the lever operation after the wire rope is taken up around the winch drum over one rotation. The lever operation was made to change linearly as shown in Fig. 8. The winch drum angular velocity is

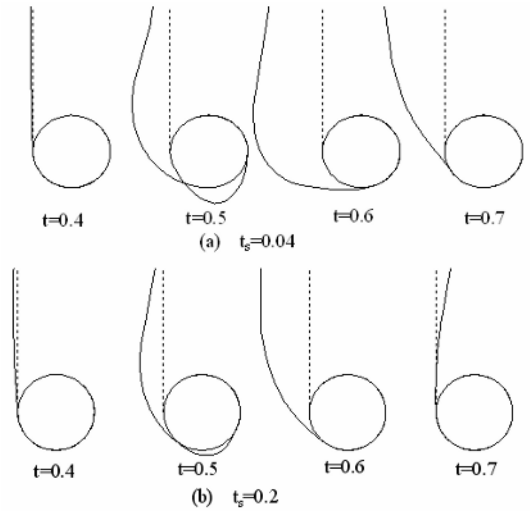

Fig. 11. Stick diagram of the wire rope at winch rapid stop.

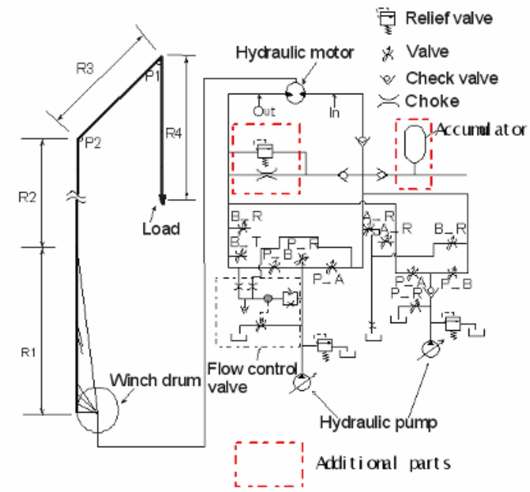

Fig. 12. Mathematical model of slow-stopping hydraulic winch system.

shown in Fig. 9. The outer pressure of the hydraulic motor is also shown in Fig. 10. Fig. 11 shows the stick diagram of the wire rope. From Fig. 11(a), we can see that the wire rope has largely shot out of the winch drum. In this case, disordered winding probably occurs because the wire rope is not in contact with the winch drum.

4. System simulation of slow-stopping hydraulic winch system

In this section, we propose a sophisticated hydraulic system for preventing disordered winding even if the winch is rapidly operated. Using above-mentioned model, the wire rope simulation are carried out for predicting the wire rope looseness. The proposed winch system model is shown in Fig. 12. This system involves a relief valve and choke valve at the outlet of the hydraulic motor that drives the winch. These valves make the outlet pressure of the hydraulic motor gentle. An accumulator is also installed at the inlet of the hydraulic motor for preventing cavitations.

The simulation for this system are carried out in the cases that the relief valve is only installed (Case 1) and the choke valve is also installed (Case 2). The simulation results of the angular velocity change of the winch drum and the pressure change of the motor outlet are shown in Figs. 13, 14. The stick diagram of the wire rope is shown in Fig. 15. In Case 1 the looseness of the wire rope occurs as shown in Fig. 15(a) in order that the deceleration of the winch drum generates at the timing that the outlet pressure is lower than

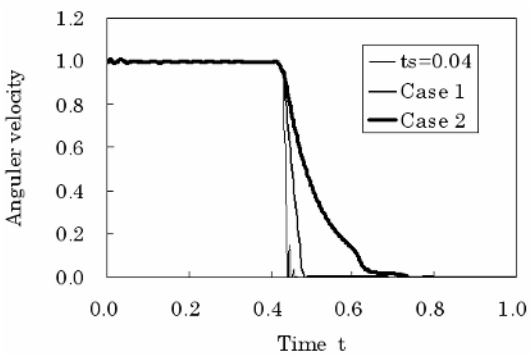

Fig.13. Angular velocity change of winch drum by using slow-stopping hydraulic winch system.

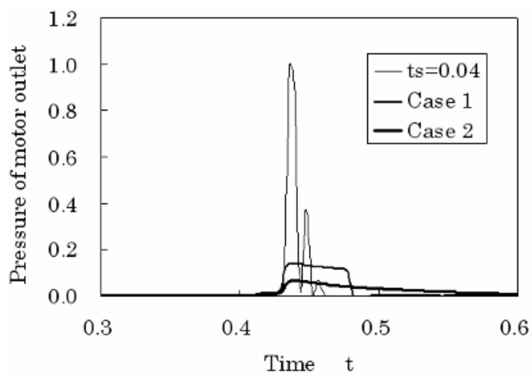

Fig. 14. Pressure change of motor outlet by using slow-stopping hydraulic winch system.

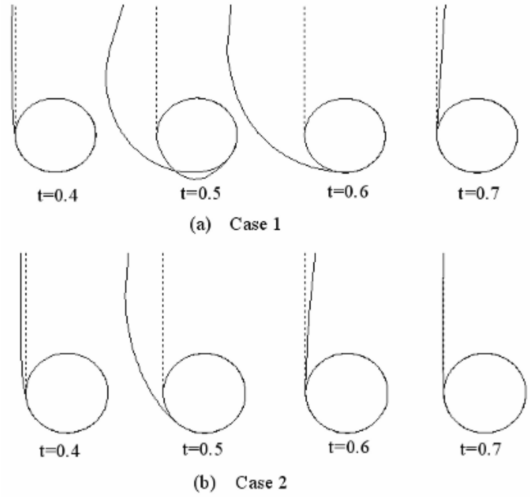

Fig. 15. Stick diagram of wire rope by using slow-stopping hydraulic winch system.

the relief pressure. In Case 2 the looseness of the wire rope does not occur as shown in Fig. 15(b) by the effect of the choke valve. It is found that the system can prevent the disordered winding.

5. Conclusions

In this paper, a dynamic simulation for wire rope on the tower crane has been described that takes into consideration not only the contact with the winch drum, but also the characteristics of the hydraulic system using SINDYS. Specifically, the following points have been demonstrated:

(1) The contact between the winch drum and wire rope can be modeled by using the variable-length truss elements and the contact spring.

(2) The dynamic behavior of wire rope that occurs at hydraulic winch stopping is affected by the dynamic characteristics of the hydraulic system.

(3) A slow-stopping hydraulic winch system has been proposed, and the system can prevent disordered winding even if the winch is rapidly operated.

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References

[1] S. C. Wu and E. J. Haug, Geometric Nonlinear Substructuring for Dynamics of Flexible Mechanical Systems, *International Journal of Numerical Methods in Engineering*, 26 (1988) 2211-2226.

[2] A. A. Shabana, Flexible Multibody Dynamics: Review of Past and Recent Developments, *Multibody System Dynamics*, 1 (1997) 189-222.

[3] E. Imanishi, H. Zui, Y. Inoue and T. Fujikawa, Simulation Technique of Flexible Linkage Mechanism and Its Application to Level Luffing Control System for Cranes, *Proceedings of Advanced Mechatronics*, (1989) 365-371.

[4] E. Imanishi, T. Nanjo, E. Hirooka and Y. Inoue, Dynamic Simulation of Flexible Multibody System with Hydraulic Drive System, *Proceedings of ACMD2004*, 100011, (2004).

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