MOTION AND VIBRATION CONTROL OF THE LIFT MECHANISM OF A LADDER TRUCK

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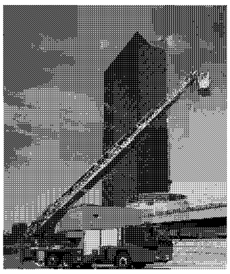
Summary A ladder truck with lift mechanism has played an important role in life-saving and fire-fighting. Although the safer and quicker operation mechanism is requested to be developed due to these demands, the lift operation generates a lot of vibration at the time of the lift operation. A coupled equation of a ladder model is derived using the differential algebraic equation. The dynamic behavior under the operation is discussed by the parameter studies.

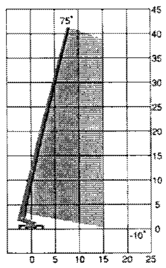
INTRODUCTION

A ladder truck with lift mechanism has played an important role in life-saving and fire-fighting for the increase of complex urban-space and high-rise building. Especially, the recent demands for the specification of a ladder truck, which are the larger load capacity of the basket at a ladder tip, the elongation of the total length and the light-weighting of a ladder itself, have been increased. However, accompanying with these trend, the lift operation generates vibrations much more and suppressing vibrations become more important problem for the quicker and safer operation mechanism.

In this paper, though an actual ladder truck is composed of four or five sections, as shown in Fig. 1, a two-sections ladder model is investigated to make the physical understanding on the dynamic behavior of a flexible ladder easier. A coupled equation of motion for the two-sections ladder model is derived using the differential algebraic equation (DAE). Performing the numerical simulation studies taking the dimensions of the two-sections flexible ladder model as parameters, how the dimensions of a ladder affect on the occurrence of vibrations is made to be clear. And the vibration control is investigated on the modification of the input driving motion of a ladder. Moreover, the optimal control method for minimizing the vibration and the required moving time of a ladder simultaneously is discussed.



(a) Photograph of an actual ladder truck



(b) Working area of the ladder

Fig. 1: Example of an actual ladder truck for the object of simulation analysis

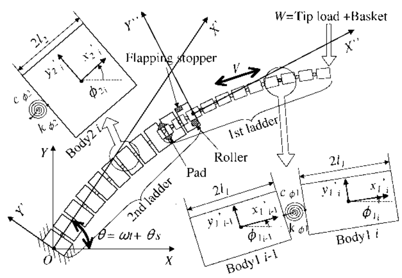


Fig. 2: Mechanical model of the 2 sections ladder

ANALYSIS METHOD

Figure 2 shows the mechanical model of the two-sections ladder. The 1st and 2nd ladder-sections are divided into n equivalent rigid bodies respectively (hereafter called "body"). The rotational springs which are equivalent to their flexual rigidity and structural damping are installed at each joint between bodies (hereafter called "hinge"). Therefore, the 1st and 2nd ladder-sections are composed of a combination of bodies, rotational springs and dampers.

The local coordinate $X'-Y'$ is defined at the bottom point of the 2nd ladder-section which can rotate with an angular velocity around the fixed point O at the bottom of the 2nd ladder-section. Furthermore, the local coordinate $X''-Y''$ is defined at the tip point of the 2nd ladder-section. The ascending and descending motions and the turning motion can rotate around Z-axis and Y-axis respectively. The extending and retracting motions can move with a velocity V along the X''-axis.

The kinematic constraint equation $\mathbf{\Phi}^{\mathsf{K}}_{2_{(i-1),i}}$ between the $(i-1)$th body and ith body of the 2nd ladder-section can be obtained in the following equation:

$$\mathbf{\Phi}^{\mathsf{K}}_{2_{(i-1),i}}=\left\{\begin{array}{l} x_{2_i}-x_{2_{i-1}}-l_2\cos\phi_{2_i}-l_2\cos\phi_{2_{i-1}} \\ y_{2_i}-y_{2_{i-1}}-l_2\sin\phi_{2_i}-l_2\sin\phi_{2_{i-1}} \end{array}\right\}=\mathbf{0} \tag{1}$$

When the 2nd ladder-section is subjected to the ascending and descending motions rotating with an angular velocity ω around Z'-axis at the fixed point O, the driving constraint equation $\mathbf{\Phi}^{\mathsf{D}}_{2,\mathsf{AD}}$ is given as follows:

$$\mathbf{\Phi}^{\mathsf{D}}_{2,\mathsf{AD}}=\left\{\begin{array}{c} x_{2_1}-l_2\cos(\omega t+\theta_{\mathsf{s}}) \\ y_{2_1}-l_2\sin(\omega t+\theta_{\mathsf{s}}) \\ \phi_{2_1}-(\omega t+\theta_{\mathsf{s}}) \end{array}\right\}=\mathbf{0} \tag{2}$$

Similarly, the diving constraint equation $\mathbf{\Phi}^{\mathsf{D}}_{2,\mathsf{T}}$ under the turning motion is also obtained. Moreover, when the two-sections ladder is extending or retracting with a velocity V, the driving constraint equation $\mathbf{\Phi}^{\mathsf{D}}_{1}$ can be defined.

The equation of motion using the differential algebraic equation(DAE) as for the two-sections flexible ladder model is described as follows:

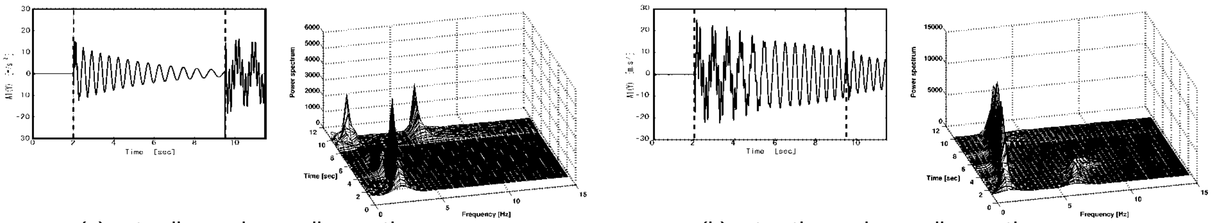
$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{\Phi}_{\mathrm{q}}{}^{\mathrm{T}} \\ \boldsymbol{\Phi}_{\mathrm{q}} & \boldsymbol{0} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{q}} \\ \boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{Q} \\ \boldsymbol{\gamma} \end{Bmatrix}, \tag{3}$$

where $\boldsymbol{q}$ is the total generalized coordinate, $\boldsymbol{M}$ the total mass matrix, $\boldsymbol{\Phi}$ the total constraint equation, $\boldsymbol{Q}$ the total generalized equation, λ the Lagrange multipliers and $\boldsymbol{\gamma}$ the function of $\boldsymbol{\Phi}$ and $\boldsymbol{q}$.

NUMERICAL SIMULATION

Extending and ascending motions simultaneously and retracting and ascending motions simultaneously

These simultaneous motions are carried out with an extending and retracting velocity $V = 1[m/s]$ and an ascending angular velocity $\omega = 0.07[rad/s]$. And, the profile of the input driving motion is an impulse-type shape as after-mentioned. Figure 3 shows the time history waves and the power spectrum.



(a) extending and ascending motions (b) retracting and ascending motions

Fig. 3: Time history waves and power spectrum of tip acceleration

Control of input driving motion of a ladder

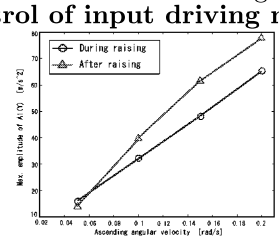
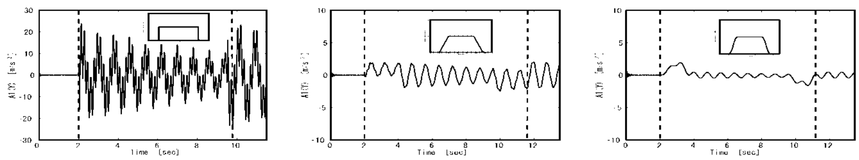


Fig. 4 Influence of ascending angular velocity on tip acceleration



(a) Impulse-type input (b) Trapezoid-type input (c) Secondary function-type input

Fig. 5: Tip acceleration under ascending motion

Figure 4 shows the influence of the angular velocity at the ascending motion. To control the motion and vibration of an actual ladder truck, let us regulate the profile of the input driving motion of a ladder in advance as feed-forward control. Figure 5 shows the time history waves under the ascending motion when the profile of the input driving motion is adjusted to the three kinds of types, impulse-type, trapezoid-type and secondary function-type.

DISCUSSION

The vibration of a ladder is found to be suppressed for the combination of the extending and other rotating motions. On the contrary, it is found to be amplified for the combination of the retracting and other rotating motions. This dynamic behavior is considered to be due to the phenomena which is called as "spaghetti problem", and to be affected much by the Coriolis' force.

Moreover, the control of the input driving motion of a ladder can be said to be important for reducing the vibration under the lift operation. The optimal control for minimizing the vibration and the required moving time is thought to be necessary for developing the ladder truck with the safer and quicker lift mechanism.

CONCLUSIONS

The following is concluded from the above-mentioned considerations and discussions;

- The proposed analysis method is proved to be useful for simulating the dynamic behavior of the two-sections ladder under the extending and retracting motions, the ascending and descending motions, and the turning motion.
- The extending motion is found to suppress the vibration generated by the rotating motions such as the ascending, descending and turning. On the contrary, the retracting motion to amplify the vibration.
- The control of the input driving motion of a ladder is clarified to have much influence on minimizing the vibration of a ladder.

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