Driving Force Control for Suppression of Tractor’s Dynamic Pitching Angle

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Keywords: Tractor, Traveling simulation, Torque control, Prevent accident, Suppression for attitude angle

In recent years, Japan’s agricultural industry has had the highest mortality rate among all other industries. The agricultural industry has also become one of the most dangerous in other countries, and this is becoming a serious problem worldwide. In Japan, the highest number of fatalities (approximately 100 fatalities per annum) result from accidents involving tractors, with the most common being rollovers. Overturning accidents can occur either when a tractor is traveling along sloped, rough terrain because the uneven road surface increases the dynamic pitch angle beyond the overturning limit, or when the operator loses control as a result of the front wheels bouncing. To prevent these accidents, it is important to control the pitch angle when traveling along such terrain. In a previous study on the attitude stabilization of vehicles while they are being driven, attitude control technology using driving torque was developed. This technology improves riding comfort in automobiles traveling along paved roads. By applying such control to a tractor, it is expected that pitching overturn accidents can be prevented. In this scenario, it is important to confirm the dynamic effect on the pitching suppression by driving torque control. Overall, in this study, a three degrees-of-freedom, vertical, pitching, and forward/backward movement behavior model of a tractor that considers the influence of the driving force on the pitch angle was developed. The reaction force that each wheel received from the road surface was calculated, and numerical calculations were performed for the acceleration along each degree of freedom. The feedback control system had a static pitch angle on the input terrain as the target value, which was applied to the model. In the control system, using PID control, the driving force was calculated from each term (proportional, integrated, and derivative) of deviations, which consist of the difference between the target value and the dynamic pitch angle. The coefficients of the PID system were determined to become effective for this condition. The limits of the driving force were set according to the specification value of the tractor engine power and the power required for slope climbing. Driving simulation using the topographic information on a site of an actual tractor overturn accident was performed with both the driving-force control model and the constant-speed traveling model. The suppression of the pitch angle by controlling the driving force was examined through a comparative analysis of the results. The pitch angle of the driving-force control model was smaller than that of the constant-speed traveling model, enabling travel along the terrain. Thus, dynamic pitch angle control was implemented and validated. The maximum pitch angle of the driving-force control model was approximately 10% smaller than that of the constant-speed traveling model. In addition, a driving force corresponding to the attitude was generated within the usable driving-force range. Pitch angle suppression was confirmed by controlling the driving force. In our study, driving simulation using topographical information on the actual accident site was conducted to examine the suppression of the dynamic pitch angle by driving-force control. Consequently, the pitch angle of the driving-force control model enabled travel along the terrain. The maximum pitch angle of the control model was approximately 10% smaller than that of the constant-speed traveling model. The results suggest that the attitude angle can be suppressed by driving-force control to prevent tractor rollover accidents.
Driving Force Control for the Suppression of the Dynamic Pitching Angle of Tractors

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ABSTRACT

In recent years, Japan’s agricultural industry has had the highest mortality rate among all other industries. Further, the agricultural industry has become one of the most dangerous in other countries; this is becoming a serious problem worldwide. In Japan, the highest number of fatalities (approximately 100 fatalities per annum) are due to accidents involving tractors, with the most common being rollovers. Overturning accidents can occur either when tractors are traveling along a sloped, rough terrain because uneven road surfaces increase the dynamic pitch angle beyond the overturning limit, or when the operator loses control owing to the bouncing of the front wheels. To prevent these accidents, the pitch angle should be controlled when traveling along such terrains. By applying attitude control using driving torque to a tractor, pitching overturn accidents could be prevented. In such scenarios, the dynamic effect on the pitching suppression by driving torque control should be verified. Overall, in this study, a three degrees-of-freedom, vertical, pitching, and forward/backward movement behavior model of a tractor that considers the influence of the driving force on the pitch angle was developed. The feedback control system had a static pitch angle on the input terrain as the target value, which was applied to the model. In the control system, using Proportional-Integral-Differential (PID) control, the driving force was calculated from each term (proportional, integrated, and derivative) of deviations, which comprises the difference between the target value and the dynamic pitch angle. The coefficients of the PID system were effective under this study’s condition (mechanical specifications and topographical information, etc.). The limits of the driving force were set according to the specification value of the tractor engine power and power required for slope climbing. A driving simulation using the topographic information on a site of an actual tractor overturn accident was conducted with both the driving-force control and constant-speed traveling models. The suppression of the pitch angle by controlling the driving force was examined through a comparative analysis of the results. The pitch angle of the driving-force control model was smaller than that of the constant-speed traveling model, enabling travel along the terrain. Thus, dynamic pitch angle control was implemented and validated. The maximum pitch angle of the driving-force control model was approximately 10% smaller than that of the constant-speed traveling model. In addition, a driving force corresponding to the attitude was generated within the usable driving-force range. Pitch angle suppression was confirmed by controlling the driving force. In our study, a driving simulation using topographical information on the actual accident site was conducted to examine the suppression of the dynamic pitch angle by driving-force control. Consequently, the pitch angle of the driving-force control model enabled travel along the terrain. The maximum pitch angle of the control model was approximately 10% smaller than that of the constant-speed traveling model. The results suggest that the attitude angle can be suppressed by controlling the driving force to prevent tractor rollover accidents.

Keywords: Tractor, Traveling simulation, Torque control, Prevent accident, Suppression for attitude angle

1. INTRODUCTION

In recent years, with the development of agricultural machinery, working efficiency has considerably improved and labor burden significantly reduced. However, there are approximately 350 annual cases of fatal farm accidents in Japan, indicating a high accident rate (JMAFF, 2019). In addition, the fatal
The injury rate per 100,000 farmers is as high as 24.0 people in the US (USDL, 2017), 16.1 people in Japan (JMAFF, 2015), and 9.2 people in the UK (HSE, 2019). Thus, in advanced countries with mechanized agriculture, agricultural injury rates are at a high level compared with other industries. This indicates that there may be more lives being lost in areas even beyond the scope of the surveys. The agricultural industry is becoming the most dangerous industry among all industries, increasingly becoming a serious problem worldwide. Therefore, taking adequate measures to reduce the fatalities is not only an important issue but also an urgent issue.

In Japan, the highest number of fatalities (approximately 100 fatalities per annum) is due to tractor accidents and the most common cause is overturning of tractors. Because of the terrain, most tractors in Japan have to travel on rough and steep slopes. This can increase the dynamic pitching angle with the risk of exceeding the overturn angle or steering control loss. To prevent such fall accidents of tractors, it is important to control the pitching angle when traveling on rough and steep terrains. This is achieved by applying the attitude control technology that inputs the driving torque to the tractor. However, it is important to verify theoretically the pitching suppression effect.

Previous studies on tractor behavior have analyzed the simulation of tractor stability on a rigid slope (Li et al., 2016) and impact dynamics model for nonlinear bouncing of tractors (Watanabe et al., 2017). Further, an analysis of tractor pitching based on an actual accident site (Matsui et al., 2016) has also been conducted. In addition, for vehicles traveling on paved roads, research on how to vary the drive torque and stabilize the vehicle attitude to improve driving comfort has been conducted (Takahashi et al., 2016, Sugai, 2016, Sawada et al., 2005). However, although there are studies on behavior stability analysis of tractors and posture stabilization in vehicles traveling on pavements, there are a few studies on posture stabilization in agricultural machines traveling on agricultural roads (rough and steep slopes). Therefore, in this study, a dynamic simulator of a tractor with three degrees of freedom (vertical, pitching, and horizontal) was developed, considering the influence of driving force on pitching. The feedback control system was applied to the model (dynamic simulator) and static pitching angle on the input terrain was set on the target value for the system. The driving force control and constant speed models were run using topographical information of the actual accident site, the results were compared, and the pitching angle suppression effect by the driving force control was examined.

2. MATERIALS AND METHODS

Dynamic equations with three degrees of freedom (vertical, pitching, and horizontal) for the tractor were formulated considering the influence of the driving force on the pitching. The behavior model of the tractor is shown in Fig. 1.

Figure 1. Behavior model of the tractor
Equations (1) to (3) provide the dynamic equations for the three degrees of freedom for the tractor. Equations (4) and (5) provide the wheel reaction and driving forces, respectively.

\[
\begin{align*}
M \ddot{z} &= M g - (R_{fr} + R_{fl} + R_{rr} + R_{rt}) \cos \varphi + \gamma (R_{fr} + R_{fl} + R_{rr} + R_{rt}) \sin \varphi - F_d \sin \varphi \\
I_y \ddot{\phi} &= (R_{fr} + R_{fl}) L_f - (R_{rr} + R_{rt}) L_r - \gamma (R_{fr} + R_{fl} + R_{rr} + R_{rt}) L_g + F_d L_g \\
M \ddot{x} &= F_D \cos \varphi - \gamma (R_{fr} + R_{fl} + R_{rr} + R_{rt}) \cos \varphi - (R_{fr} + R_{fl} + R_{rr} + R_{rt}) \sin \varphi \\
R_{ij} &= (z + L_i \varphi) k_i + (\dot{z} + L_i \dot{\varphi}) c_i \\
F_D(t) &= K_p e(t) + K_i \int e(t) \, dt + K_d \frac{de(t)}{dt}
\end{align*}
\]

where,
\[
\begin{align*}
M &= \text{Mass of body [kg]}, \quad F_D = \text{Driving force [N]}, \quad R = \text{Reaction force of wheel [N]}, \\
I_y &= \text{Inertia moment of pitching [kg \cdot m^2]}, \quad k = \text{Spring coefficient [N/m]}, \\
c &= \text{Damping coefficient [N \cdot s/m]}, \quad g = \text{Gravity acceleration [m/s^2]}, \quad z = \text{Vertical displacement [m]}, \\
\varphi &= \text{Pitching angle [rad]}, \quad x = \text{Horizontal displacement [m]}, \\
L_f &= \text{Length of mass center to front axle [m]}, \quad L_r = \text{Length of mass center to rear axle [m]}, \\
L_g &= \text{Length of mass center to ground [m]}, \quad e(t) = \text{Deviation of control system}
\end{align*}
\]

Based on these dynamic equations, an original simulator using Matlab/Simulink was developed. In the simulator, the reaction force that each wheel receives from the road surface was calculated, and the acceleration for each degree of freedom was numerically calculated using the fourth-order Runge–Kutta method. The tractor specifications and model parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass [kg]</td>
<td>1050</td>
</tr>
<tr>
<td>Full length [m]</td>
<td>2.98</td>
</tr>
<tr>
<td>Full width [m]</td>
<td>1.32</td>
</tr>
<tr>
<td>Total height [m]</td>
<td>1.93</td>
</tr>
<tr>
<td>Wheel base [m]</td>
<td>1.5</td>
</tr>
<tr>
<td>Distance of mass center and ground [m]</td>
<td>0.91</td>
</tr>
<tr>
<td>Distance of mass center and rear axle [m]</td>
<td>0.65</td>
</tr>
<tr>
<td>Kp [-]</td>
<td>100</td>
</tr>
<tr>
<td>Ki [-]</td>
<td>280</td>
</tr>
<tr>
<td>Kd [-]</td>
<td>20</td>
</tr>
<tr>
<td>Inertia moment of pitching [kg \cdot m^2]</td>
<td>600</td>
</tr>
<tr>
<td>Front wheel spring coefficient [N/m]</td>
<td>60000</td>
</tr>
<tr>
<td>Front wheel damping coefficient [N \cdot s/m]</td>
<td>200</td>
</tr>
<tr>
<td>Rear wheel spring coefficient [N/m]</td>
<td>160000</td>
</tr>
<tr>
<td>Rear wheel damping coefficient [N \cdot s/m]</td>
<td>4400</td>
</tr>
</tbody>
</table>

The specifications used catalog values of a 30-horsepower tractor; further, the spring coefficient, damping coefficient, and moment of inertia used the values measured experimentally (Aoyagi et al., 2016).

A control system diagram is shown in Fig. 2. In the control system, using PID control, the driving force was calculated from each term (proportional, integrated, and derivative) of deviations, which comprises the difference between the target value and the dynamic pitch angle. As for control parameters, Kp, Ki, and Kd were searched in the range 1–500, respectively, and the most effective parameters of suppressing the maximum pitching angle were determined for the conditions assumed in this study. The limits of the driving force were set according to the specification value of the tractor engine power and power required for slope climbing.
For a simulation using the topographical information of actual accident site, we conducted a survey and hearing considering a tractor fall accident site that occurred in Niigata Prefecture in 2013 (Fig. 3).

As for how the actual accident occurred, when the tractor climbed up on a farm road with a slope of about 20° at a traveling speed of about 1.0 m/s, the front wheel of the tractor bounced up and fell to the right near the middle of the slope. The input topography was reproduced by adding measured surface roughness to spline interpolation of the topography data obtained by surveying (Fig. 4).
The driving simulation was conducted with the driving force control model and constant speed model, the results were compared, and the pitching angle suppression effect by the driving force control was examined.

3. RESULTS AND DISCUSSION

Fig. 5 shows the pitching displacement of the pitching angle control and constant speed models (1.0 m/s). The control effect (suppressed pitch angle) can be confirmed by observing that compared with the constant speed model, the pitching angle is suppressed for the control model. In particular, the control effect is remarkable in the traveling distance between 30 m and 40 m. The maximum pitching angle is 18.4° for the control model and 21.0° for the constant speed model around the traveling distance of 40 m. The maximum pitching angle of the control model is approximately 88% of the maximum pitching angle of the constant speed model.

Fig. 6 shows the increasing and decreasing of the pitching angle (the difference between the dynamic attitude angle and the static attitude angle) compared with the static pitching angle. Fig. 6 shows that the pitching angle is increased to a maximum of 3.7° in the control model and the pitching angle is increased at a maximum of 7.7° in the constant speed model. Moreover, the RMS value of each pitching angle increase/decrease in the travel distance between 15 m and 45 m (climbing section) is 1.9° in the control model and 2.6° in the constant speed traveling model; further, it travels more parallelly to the topography in the control model (showing a pitching angle close to the static attitude angle).

Fig. 7 shows the driving force displacement of the pitching angle control model. The figure also shows that the driving force in the control model corresponds to the posture. This indicates the possibility of effectively controlling attitude by controlling the driving force according to the attitude angle.
From the above research, the suppression effect of the dynamic pitching angle by the driving force control is examined by the driving simulation based on topographical information of the actual accident site. The pitching angle suppression effect is obtained by controlling the driving force, and it was possible to travel along the terrain compared with the constant speed model. In addition, it was shown that the maximum pitching angle of the control model was approximately 10% lower than the maximum pitching angle of the constant speed model under the conditions of this study. From this, the possibility of attitude angle suppression by driving force control for fall accident prevention was demonstrated.

4. CONCLUSION
Farm work accidents are a global issue. In Japan, the most common agricultural accident is the overturning of tractors, which require the most urgent mitigating measures. The stabilization of the posture of the tractor by drive torque control is expected to prevent pitching overturn, and it is important to theoretically verify the pitching suppression effect. In this study, a dynamic simulator with three degrees of freedom (vertical, pitching, and horizontal) of a tractor was developed considering the influence of the driving force on the pitching. The feedback control system was applied to the model (dynamic simulator) and static pitching angle on the input terrain was set on the target value for the system. The driving force control and constant speed models were run using the topographical information of the actual accident site; the results were compared, and the pitching angle suppression effect by the driving force control was examined.

As a result of this simulation, the pitching angle of the control model could be suppressed (traveling along the terrain) compared with that of the constant speed model, and the control effect can be confirmed. Furthermore, the maximum pitching angle is 18.4° for the control model and 21.0° for the constant speed model; the maximum pitching angle of the control model is about 10% lower than the constant speed model. In addition, the pitching angle of the control model rises 3.7° with respect to the static attitude and pitching angles of the constant-speed travel model rises at 7.7°, and the driving force according to the attitude is generated in the control model.

From the above research, the suppression effect of the dynamic pitching angle by the driving force control was examined by the driving simulation based on the topographical information of the actual accident site. The pitching angle suppression effect was obtained by controlling the driving force, and it was possible to travel along the terrain compared with the constant speed model. In addition, it was shown that the maximum pitching angle of the control model was about 10% lower than the maximum pitching angle of the constant speed model under the conditions of this study. From this, the possibility of attitude angle suppressing by driving force control for fall accident prevention was demonstrated.

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