Computation of Tipping over Stability Criterion using ZMP algorithm for Hydraulic Excavator having Crane Function

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Abstract: This paper deals with tipping over of hydraulic excavator’s crane work. If the excavator lifts too heavy weight, the excavator will be tipped up. This is account for 38% of whole excavator accidents. In this paper, tipping-over load which is maximum load of excavator can lift with displacement of excavator links, real load and tipping-over rate are computed with Zero Moment Point theory. ZMP is verified with simulation and experiment.

Keywords: Hydraulic Excavator, Tipping-over rate, Zero Moment Point

1. INTRODUCTION

Nowadays, not only excavating works using hydraulic excavators but also crane works for the relatively light objects using same devices are conducted in the construction site. But in my country crane works using the hydraulic excavators are prohibited by the law. Nevertheless, the works are conducted illegally when necessary. Therefore, accidents due to this problem are increasing and account for 38% of the total excavator-related accidents.

In developed nations, the necessity for the crane function in the construction site is so high that the governments lead this subject. Especially, in Japan the mobile crane-attached hydraulic excavator was developed in early 1980s and the recognition of the necessity for the crane work was increased because of the article 164 in Japan Labor Safety and Sanitation Law. Japan Crane Association formally enacted the JCA standards in June, 1998 so they could apply the crane function to the excavator more safely.

As stated above, in developed countries hydraulic excavators having crane function are commercialized and applied to lots of fields. But, in my country it is true that crane works are conducted without proper safety devices, posing a lot of threat to the operators. Therefore, to reduce the accident rate in the workplace the tipping-over rate should be determined legally and crane works with the hydraulic excavators also should be commercialized.

Zero Moment Point (ZMP) theory was applied to judge the tipping-over stability while conducting the crane work using the hydraulic excavator. Generally, moment equilibrium equations in static state are applied to determine the tipping-over rate. However, in this case dynamic characteristics of the hydraulic excavators are excluded from determining the stability, so it is impossible to determine the tipping-over stability for the dynamic characteristics. But dynamic characteristics generated during the work as well as the static characteristics can be considered to determine the stability if ZMP theory is applied. So, it is thought that ZMP theory is applicable to the tipping-over stability computation algorithm for the hydraulic excavators.

We designed the tipping-over stability criterion algorithm considering the dynamic characteristics to which ZMP theory is applied and discussed the usefulness of the proposed algorithm compared with the moment equilibrium equation through the simulation and the actual test.

2. MODELING OF THE HYDRAULIC EXCAVATOR

2.1 Position locus of the working device

During the crane works using the hydraulic excavators the coordinate systems are established to describe the motion of the working device in Fig. 1.

![Fig. 1 Coordinates of Excavator](image)

The end position locus of the working device consisting of boom, arm and bucket is written as the function of the angular displacement of the working components.

- **Boom:** \( x_b = L_b \sin \theta_b, y_b = L_b \cos \theta_b \)
- **Arm:** \( x_a = x_b + L_a \sin(\theta_a + \theta_b), y_a = y_b + L_a \cos(\theta_a + \theta_b) \)
- **Bucket:** \( x_k = x_a + L_k \sin(\theta_a + \theta_b + \theta_k), y_k = y_a + L_k \cos(\theta_a + \theta_b + \theta_k) \) (1)
2.2.1 Frame
Mass center of the upper and the lower frames are constant.

\[ x_{ig} = C_1, y_{ig} = C_2, x_{2g} = C_3, y_{2g} = C_4 \] (2)

2.2.2 Boom

\[ x_{ig} = l_1 \sin(\theta_e - \delta_t), y_{ig} = l_3 \cos(\theta_e - \delta_t) \] (3)

2.2.3 Arm

\[ x_{ig} = x_5 + l_5 \sin(\theta_e + \theta_a - \delta_4), y_{ig} = y_5 + l_5 \cos(\theta_e + \theta_a - \delta_4) \] (4)

2.2.4 Bucket

\[ x_{ig} = x_5 + l_5 \sin(\theta_e + \theta_a + \delta_4), y_{ig} = y_5 + l_5 \cos(\theta_e + \theta_a + \delta_4) \] (5)

2.2.5 Boom Cylinder

\[ x_{ig} = X_{acu} + X_{hec}, y_{ig} = Y_{acu} + Y'_{hec} \]

\[ x_{ig} = l_6 \sin(\theta - \delta_3 - \alpha), y_{ig} = l_6 \cos(\theta - \delta_3 - \alpha) \]

\[ \alpha = \cos^{-1}\left(\frac{l_6^2 + l_{63}^2 - l_{10}^2}{2l_6 l_{63}}\right) \] (6)

2.2.6 Arm Cylinder

\[ x_{ig} = l_1 \sin(\theta_e - \delta_t), y_{ig} = l_1 \cos(\theta_e - \delta_t) \] (7)

2.2.7 Bucket Cylinder

\[ x_{ig} = x_6 + l_6 \sin(\theta_e + \theta_a - \delta_a) \]

\[ y_{ig} = y_6 + l_6 \cos(\theta_e + \theta_a - \delta_a) \] (8)

2.2.8 Bucket Link

\[ x_{ig} = x_6 + l_6 \sin(\theta_e + \theta_a - \delta_a) \]

\[ y_{ig} = y_6 + l_6 \cos(\theta_e + \theta_a - \delta_a) \] (9)

2.2.9 Control Rod

\[ x_{ig} = x_6 + l_6 \sin(\theta_e + \theta_a - \delta_a) \]

\[ y_{ig} = y_6 + l_6 \cos(\theta_e + \theta_a - \delta_a) \] (10)

2.2.10 Weight

\[ x_{ig} = x_6 + l_{11} \sin(\theta_e + \theta_a + \delta_{11}) \]

\[ y_{ig} = y_6 + l_{11} \cos(\theta_e + \theta_a + \delta_{11}) \] (11)

3. TIPPING-OVER STABILITY CRITERION
ALGORITHM

3.1 Zero Moment Point (ZMP)

Zero Moment Point (ZMP) is defined as the point on the surface where the total moment of the system inertia force, the gravity and the external forces to the standard coordinate of the target system's lower body surface. In fig. 3, if D'Alembert’s law is applied to the point P, you can derive the equation of motion and it is

\[ \sum_{i} (r_i - P) \times m_i (\ddot{r}_i + g + \ddot{p}) + \rho_c \times m_i \ddot{p} + \sum_{j} T_j - \sum_{j} M_j 
- \sum_{k} (s_k - p) \times f_k = M_p \]

3.2 ZMP applied tipping-over rate computation

In ZMP-applied stability analysis we establish the range of the stability region. If ZMP is out of the established range, it is unstable and if ZMP is within the range, it is stable. The stable region is defined as the region which does not consider the
disturbance; the stable region is the region considering the disturbance.
During the crane work using the hydraulic excavator the stable region defined by ZMP theory is the lower body surface supporting the hydraulic excavator. If you consider the disturbance generated in the working environment, the effective stable region will be the internal lower-body surface in the hydraulic excavator.

3.2.1 Tipping-over Load
If ZMP theory based on the mathematical model described in Chap. 2 is applied to get the value of the tipping-over load, the tipping-over load will be
\[
x_i = \frac{\sum_{i=1}^{10} m_i (y_{ig} + g) \sum_{i=1}^{10} m_i x_{ig} x_{mg} - x_{zmp} \sum_{i=1}^{10} m_i (y_{ig} + g)}{x_{zmp} (y_{mg} + g) + x_{mg} y_{mg} - (y_{mg} + g) x_{mg}}
\]
(14)
Where, \( m_i \) = each component’s mass
\( x_{i}, y_{i} \) = The position coordinates value of the each Component
\( x_{mg}, y_{mg} \) = The position coordinates value of the load
\( g \) = Acceleration of gravity.

3.2.2 Pull-up Load
The boom cylinder supports the pull-up load and the load of the working device on the supporting point of the hydraulic excavator’s main body. Considering the supporting force, the moment equilibrium equation is applied to the boom joint as a standard point.
The pull-up load equation is
\[
W = \frac{F_y L_b - \sum_{i=3}^{10} m_i x_{ig}}{x_{mg}}
\]
(15)
Where, \( F_y = P_h A_h - P_r A_r, L_b = l_b \sin \alpha \).
\( P_h, P_r \) = Pressure on the head & rod of the boom cylinder,
\( A_h, A_r \) = area on the head & rod.

3.2.3 Tipping-over rate
The tipping-over rate is the ratio of the tipping-over rate to the pull-over rate and represents the tipping-over occurrence rate as the percent (%).

4. SIMULATION AND EXPERIMENT
Simulations and the experiment with hydraulic excavator are carried out to compute the tipping-over rate and verify the proposed ZMP theory. The condition is to hang the load under the hydraulic excavator and unfold the working device parallel to the ground, which is shown in Fig. 4. The two kinds of load masses are 0.5t, 1t respectively. Because of the structure of the hydraulic excavator, the area which contacts the ground is minimum when the driver seat is vertical to the track. It is the weakest case so that we calculated the tipping-over rate for this situation. The target for the simulation and actual tests is 5-ton R555M of the HHI.

Fig. 4 Work condition

4.1 Simulation
During the simulation we compare the results from ZMP theory with that from the moment equilibrium equation which is the established method to compute the tipping over rate.
Fig. 5 is the Schematic of the work in simulation and Fig. 6 is the results from the moment equilibrium equation and ZMP theory.

Fig. 5 Crane work in simulation

Fig. 6 Results of Tipping-over load by simulation
4.2 Experiment
Experiments were carried out for the loads of 0.5t and 1t respectively which is shown in Fig. 4. The end position of the working device which has the load will be plotted in (a) of Fig. 7,8 which used the \{0\} coordinate system in Fig. 1. The tipping-over load and the pull-over load is shown in (b) of Fig. 7,8. The tipping-over rate is shown in (c) of Fig. 7,8.

Fig. 7 Experiment result with 0.5[ton]

Fig. 8 Experiment result with 1 [ton]
5. CONCLUSION

The application of ZMP theory was proposed (compared with the static-state moment equilibrium equation, ZMP theory considers dynamic and static factors.) and we could verify the possibility of the application.

In actual tests, when 0.5 ton load is hanged on the end of the arm, the hydraulic excavator maintains the stability. However, when 1 ton load is hanged, the device only maintains the stability within the working radius range of 70%. We can visually see the effect of the load's dynamic factor on the tipping-over stability. We can also check that excavator body breaks away from the ground near the point expected to occur the tipping-over by the tipping-over load.

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REFERENCES