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 carne 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.

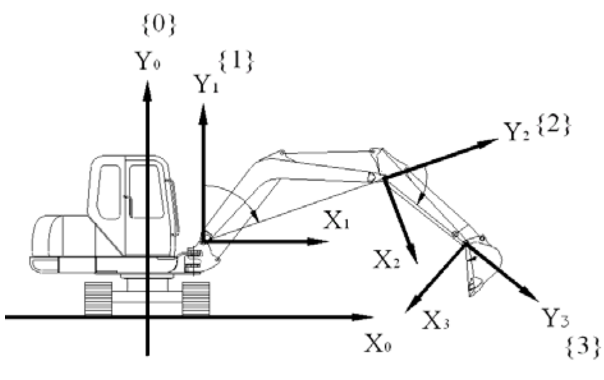


Fig. 1 Coordinates of Excavator

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 : $x_a = x_b + L_a \sin(\theta_b + \theta_a)$.
  $y_a = y_b + L_a \cos(\theta_b + \theta_a)$.
- Bucket : $x_k = x_a + L_k \sin(\theta_b + \theta_a + \theta_k)$.
  $y_k = y_a + L_k \cos(\theta_b + \theta_a + \theta_k)$ (1)

2.2 Mass center locus of the working device

Fig. 2 is the schematic to derive the mass center locus from the hydraulic excavator device.

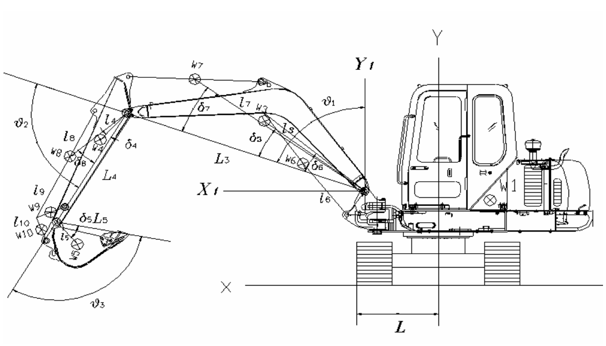


Fig. 2 Schematic of center of mass

The mass center of the each part is described as a function of the angular displacement.

2.2.1 Frame

Mass center of the upper and the lower frames are constant.

$$x_{1g} = C_1, y_{1g} = C_2, x_{2g} = C_3, y_{2g} = C_4 \tag{2}$$

2.2.2 Boom

$$x_{3g} = l_3 \sin(\theta_b - \delta_3), y_{3g} = l_3 \cos(\theta_b - \delta_3) \tag{3}$$

2.2.3 Arm

$$x_{4g} = x_b + l_4 \sin(\theta_b + \theta_a - \delta_4) \quad .$$

$$y_{4g} = y_b + l_4 \cos(\theta_b + \theta_a - \delta_4) \tag{4}$$

2.2.4 Bucket

$$x_{5g} = x_a + l_5 \sin(\theta_b + \theta_a + \theta_k - \delta_5) \quad .$$

$$y_{5g} = y_a + l_5 \cos(\theta_b + \theta_a + \theta_k - \delta_5) \tag{5}$$

2.2.5 Boom Cylinder

$$x_{6g} = X_{axis} + x'_{6g}, y_{6g} = Y_{axis} + y'_{6g} \quad .$$

$$x'_{6g} = l_6 \sin(\theta_1 - \delta_6 - \alpha), \quad y'_{6g} = l_6 \cos(\theta_1 - \delta_6 - \alpha) \quad .$$

$$\alpha = \cos^{-1}\left(\frac{l_{61}^2 + l_{63}^2 - l_{62}^2}{2 l_{61} l_{63}}\right) \quad .$$

$$l_{63}^2 = l_{61}^2 + l_{62}^2 - 2 l_{61} l_{62} \cos(2\pi - A + \delta_6 - \theta_1) \tag{6}$$

2.2.6 Arm Cylinder

$$x_{7g} = l_7 \sin(\theta_1 - \delta_7), y_{7g} = l_7 \cos(\theta_1 - \delta_7) \tag{7}$$

2.2.7 Bucket Cylinder

$$x_{8g} = x_b + l_8 \sin(\theta_1 + \theta_2 - \delta_8) \quad .$$

$$y_{8g} = y_b + l_8 \cos(\theta_1 + \theta_2 - \delta_8) \tag{8}$$

2.2.8 Bucket Link

$$x_{9g} = x_b + l_9 \sin(\theta_1 + \theta_2 - \delta_9) \quad .$$

$$y_{9g} = y_b + l_9 \cos(\theta_1 + \theta_2 - \delta_9) \tag{9}$$

2.2.9 Control Rod

$$x_{10g} = x_b + l_{10} \sin(\theta_1 + \theta_2 - \delta_{10}) \quad .$$

$$y_{10g} = y_b + l_{10} \cos(\theta_1 + \theta_2 - \delta_{10}) \tag{10}$$

2.2.10 Weight

$$x_{mg} = x_b + l_{11} \sin(\theta_1 + \theta_2 + \delta_{11}) \quad .$$

$$y_{mg} = y_b + l_{11} \cos(\theta_1 + \theta_2 + \delta_{11}) \tag{11}$$

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

$$\sum_i (r_i - P) \times m_i(\ddot{r}_i + g - \ddot{p}) + \rho_c \times m\ddot{p} + \sum_i T_i - \sum_j M_j - \sum_k (s_k - p) \times f_k = M_p$$

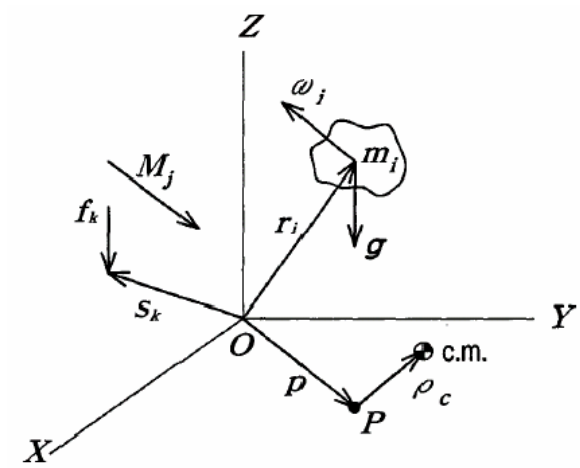


Fig. 3 Rigid body system

The position vector of the mass center to the point P is described as the equation (12). If the point P is ZMP, the position vector is $p = p_{zmp} = \lfloor x_{zmp}, y_{zmp}, 0 \rfloor_T$ and the total moment is $M_p = [0, 0, M_z]^T$.

$$\rho_c = \frac{1}{m} \sum_{m_i} m_i (r_i - p) \tag{12}$$

If there is no moment and force from the surroundings, x and y components of ZMP are

$$x_{zmp} = \frac{\sum_i m_i(\ddot{z}_i + g_z)x_i - \sum_i m_i \ddot{x}_i z_i}{\sum_i m_i(\ddot{z}_i + g_z)} \quad .$$

$$y_{zmp} = \frac{\sum_i m_i(\ddot{z}_i + g_z)y_i - \sum_i m_i \ddot{y}_i z_i}{\sum_i m_i(\ddot{z}_i + g_z)} \tag{13}$$

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

$$x_l = \frac{\sum_{i=1}^{10} m_i(\ddot{y}_{ig}+g) - \sum_{i=1}^{10} m_i \ddot{x}_{ig} y_{ig} - x_{zmp}\sum_{i=1}^{10} m_i(\ddot{y}_{ig}+g)}{x_{zmp}(\ddot{y}_{mg}+g) + \ddot{x}_{mg} y_{mg} - (\ddot{y}_{mg}+g)x_{mg}} \tag{14}$$

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

$$W = \frac{F_b L_b - \sum_{i=3}^{10} m_i x_{ig}}{x_{mg}} \tag{15}$$

Where, $F_b = P_h A_h - P_r A_r$, $L_b = l_{61}\sin\alpha$,

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.

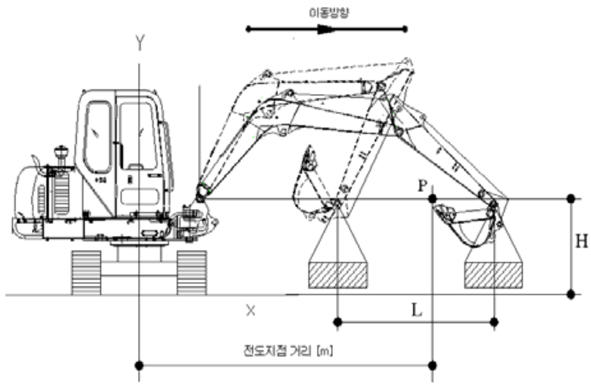


Fig. 4 Work condition

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.

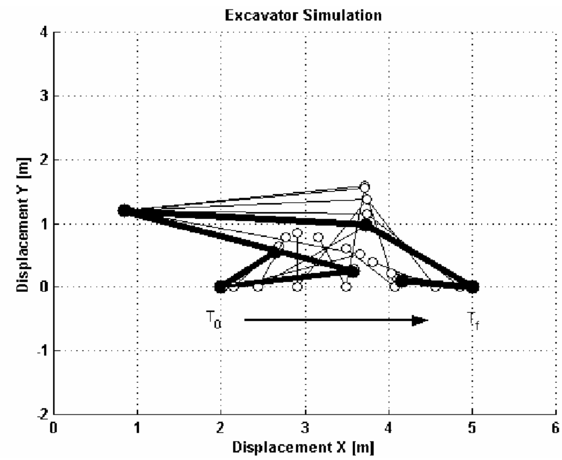


Fig. 5 Crane work in simulation

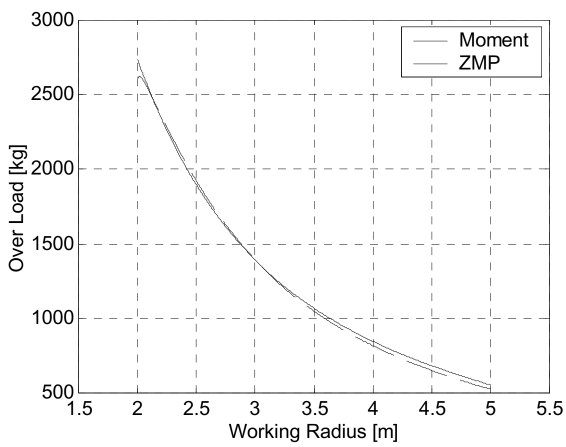
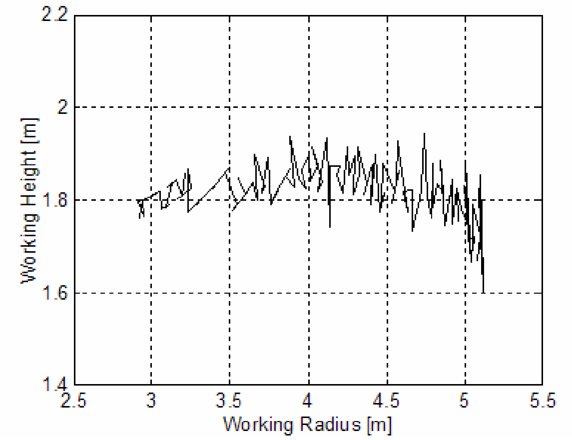


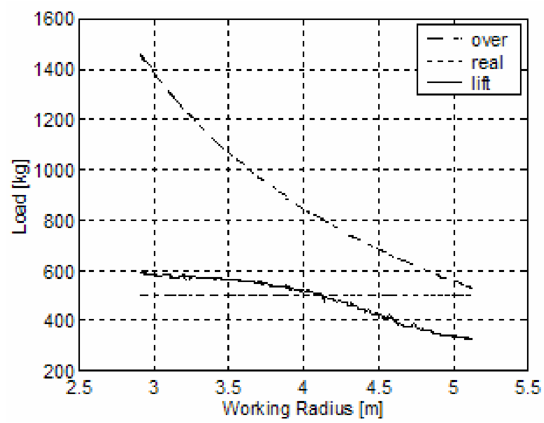
Fig. 6 Results of Tipping-over load by simulation

4.2 Experiment

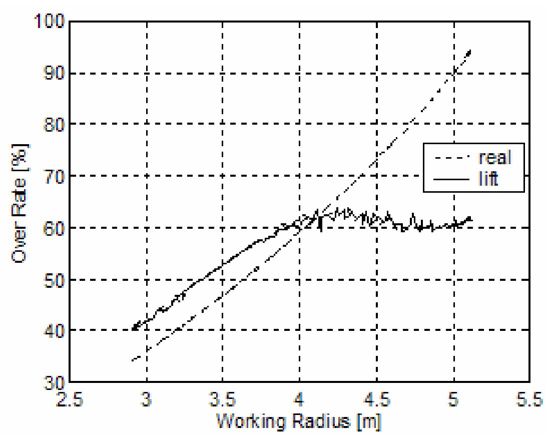
Experiments were carried out for the loads of 0.5t and 1t respectively which is shown in Fig. 4. The end position of the working device which has the load will be plotted in (a) of Fig. 7,8 which used the {0} coordinate system in Fig. 1. The tipping-over load and the pull-over load is shown in (b) of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



(a) Displacement of attachment end

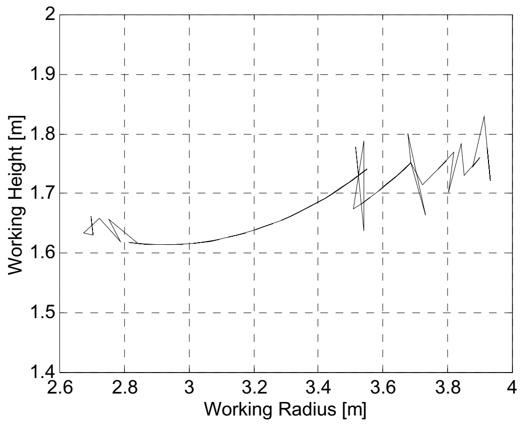


(b) Tipping-over load & Real load

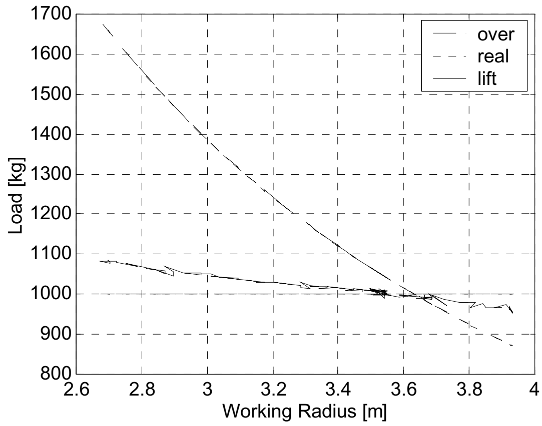


(c) Tipping-over rate

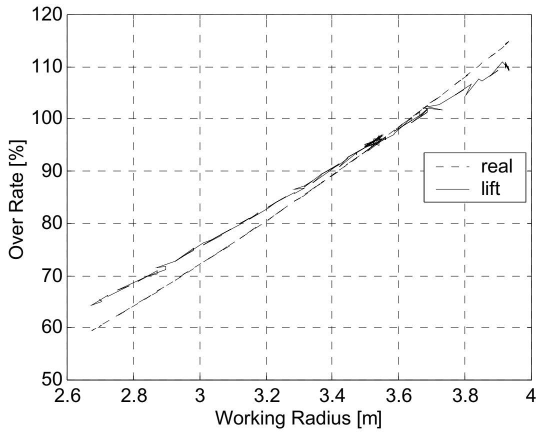
Fig. 7 Experiment result with 0.5[ton]



(a) Displacement of attachment end



(b) Tipping-over load & Real load



(c) Tipping-over rate

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 1ton 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

[1] K.Sorao, T. Murakami, and K. Ohnishi, A Unified Approach to ZMP and Gravity center Control in Biped Dynamic Stable Walking, AIM97,1997.

[2] Shigeki. SUGANO, Qiang HUANG, Ichiro KATO, Stability Criteria in Controlling Robotic Systems, IEEE/RSJ, July 26~30,1993.

[3] S.Y.Yang etc, A Study on Trafectory Tracking Control of Field Robot, ICASE, Vol.8, No.9,2002.

[4] S. Kajita, K. Tani, Study of Dynamic Biped Locomotion on Rogged Terrain, Proceedings of the IEEE International conference on Robotics and Automation, pp 1405~1411,1991.

[5] A. Ghasempoor, N. Sepehri, A Measure of Stability for Mobile Manipulators with Application to heavy-duty Hydraulic Machines, ASME, Vol.120, 1998.