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에너지안정성 레벨을 이용한 필드로봇의 안정성에 관한 연구
A Study of Stability for Field Robot using Energy Stability Level Method

웬치탄[1] · 레광환[1] · 정영만[1] · 양순용*

C. T. Nguyen, Q. H. Le, Y. M. Jeong and S.Y. Yang

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Key Words : Field Robot, Support Boundary, Equilibrium Plane, Energy Stability Level Method, Stability Margin.

Abstract: In this research, the energy stability level method is used for examining the stable state of Field Robot under effects of swing motion, at particular postures of manipulator, and terrain conditions. The energy stability level is calculated by using the dynamic models of Field Robot, subjected to the concept of equilibrium plane and support boundary. The results, simulated by using computing program for estimating the potential overturning of Field Robot, supply useful predictions of stability analysis for designers and operators.

1. Introduction

Field Robot, mentioned in this research, is a heavy construction equipment consisting of boom, arm, bucket and cab on a rotating platform, such as excavator. These machines work in various surroundings such as in the construction, transportation, agriculture and mining etc. The research of the safety for operation of such machines is meaningful. The factors affecting stability as the mass, the impact energies were studied for estimating stability characteristics of Field Robot. The aim of this research is to study the effect of internal impact energy to estimate the potential overturning of Field Robot, and applying these results for calculating parameters of automation remote control or human operator.

* Corresponding author: soonyy@ulsan.ac.kr

1 School of Mechanical and Automobile Engineering, University of Ulsan, Ulsan680-749, Korea

The stability of some other machines was researched early. The first approaches of this trend were applied for the static stability and gait generations of legged machines. In the 1970s, Robert B. McGhee [1] had defined the support pattern and margin of static stability. Basing on such margin concept, Davidson and Schweitzer [2] has applied the screw-mechanics method for building an algorithm to determine stability margin of four-legged vehicle. Messuri and Klein [3] had extended the support boundary of legged vehicle and initially study of the curves of energy level showing the same level of stability locus on the projection plane due to given support boundary. There are other approaches using the force-angle stability measurement for estimating the safety of Field Robot[4], [5]. Another method for evaluating the stability – Zero Moment Point (ZMP) – was applied for Field Robot[6], [7]. In 1998, Ghasempoor and Sepheri had presented a model include the effect of force and moment to quantify stability characteristics of 215B Caterpillar excavator based log-loader. The research of Ghasempoor [8] regards the effect of forces/moments arising from the manipulation of the implement on machine safety.

In this research, the aim is to examine stability range of excavator S015 be subject to the manipulating forces/moments of attachments, the swing of cabin, inertial effects interacting with surroundings conditions. The results were depicted by using energy method mentioned in research of Ghasempoor and calculated by applying the mathematical modeling of Koivo [9], parameters estimation of Tafazoli [10] and the dynamics stability constraints of Dubowsky [11]. The locus of gravity center position was estimated similarly with results of Jesús Morale [12]. The potential overturning of Field Robotis investigated on terrain conditions. The stability margin indicates the exerting work of the interaction with surroundings or another object. The work is over stability margin, the stability of Field Robot will be broken. Hence, this research applies the energy stability level method for evaluating stability level of Field Robot on various surroundings, the effects of inertial loading.

At first, the energy stability level method, and relative theories such as support boundary, equilibrium plane and dynamic equation of motion will be presented in section 2. In section 3, the stability level will be examined and simulated by using Matlab/Simulink.

2. The Energy Stability Level Method

The aim of this research is to study the stability of Field Robot using concept of energy stability level. The energy stability level is subject to equilibrium plane, support boundary and dynamic model of Field Robot.

The support boundary [2] of arbitrary object is a closed convex polygon consists of segments which connect the tips of the contact points projected on horizontal plane. The Field Robot runs on its tracks, so the support boundary is a simple planar rectangle with four segments.

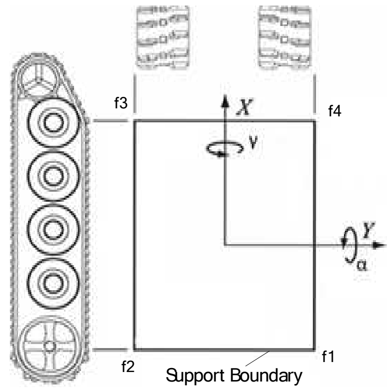

Fig. 1 Support boundary of Field Robot.

For each segment of support boundary, the respective equilibrium plane and energy stability level are determined[2], [8].

The equilibrium plane is defined as a plane containing such segment and has an orientation with respect to the vertical plane. If the body is rotated around the edge until the gravity center falls in this plane, the net moment of all present forces/moments around the edge becomes the minimum in absolute value.

The energy stability level is work required to rotate machine body (which is subject to gravitational as well as external and inertial forces/moments) about the segment, until the gravity center reaches the equilibrium plane. The minimum of energy stability levels of all segments of support boundary is the energy stability margin. If the margin is positive, that means larger than zero, the Field Robot is stable, vice versa unstable.

2.1 The Energy Stability Level

By definition of the energy stability level (ESL), the ESL for rear edge (edge f_1f_2) of support boundary, depicted in Fig. 2 is calculated as follows.

$$ESL = -(W_1 + W_2) \tag{1}$$

Where,

W_1 is the potential energy which is work done to move the gravity center from original position at angle $-\psi$ to the onset point of instability at angle ϕ, only depends on the vertical displacement of gravity center. The angle γ is a lateral inclined angle versus the longitudinal inclined angle α for down or up-hill.

$$W_1 = -mg|\vec{Q}|(\cos\phi - \cos\psi)\cos\gamma \qquad (2)$$

W_2 external kinetic energy, affected by external force and moment of attachments, is given by

$$W_2 = \int(\vec{F}\vec{R})d\theta + \int(\vec{M})d\theta \qquad (3)$$

At each instantaneous position of gravity center, we only determine an equilibrium plane or a value of angle ϕ, therefore, W_2 can be rewritten

$$W_2 = (\vec{F}\vec{R})\int d\theta + (\vec{M})\int d\theta = (\vec{F}\vec{R} + M)(\phi + \psi - \alpha) \qquad (4)$$

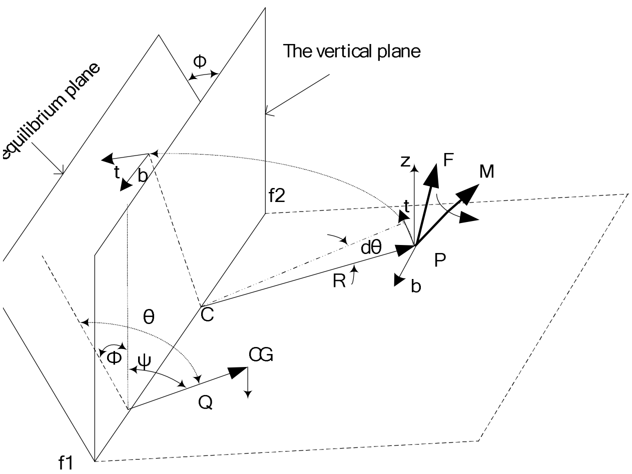

Fig. 2 The equilibrium plane and energy stability level calculation of Field Robot.

Thus the Energy Stability Level is a function of following inputs:

$$ESL = f(F, M, \phi, \psi, \alpha, \gamma)$$

Where,

F, M: are impact forces/moments calculated by dynamics of excavator.

ϕ: is the angle of the equilibrium plane.

ψ: is position angle of gravity center.

αandγ: are longitudinal and lateral slope angle used to describe the terrain condition.

R: is position vector of point there are existence of force and moment.

Q: is position vector of gravity center.

2.2 Equilibrium Plane

The equilibrium plane is the plane with two factors, one arbitrary segment of support boundary and an angle respect to the vertical plane at such segment. There are four instantaneous equilibrium planes at four edges respectively. When the gravity center is rotated from instantaneous origin point to the equilibrium plane, the net moment at support edge becomes zero and the machine is on the onset of instability. The parameter of equilibrium plane need to be determined is ϕ.

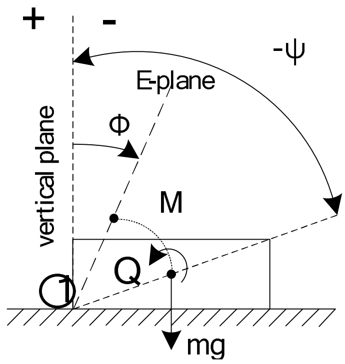

Fig. 3 The equilibrium plane.

As shown in Fig. 3, the simple equilibrium plane was considered, it means that just exist the inertial moment and gravitational force of object. Suppose that the equilibrium plane at rear edge coincides with vertical plane the ϕ angle, so that, the value of ϕ angle varies according to instantaneous moment and position of gravity center [8]. Applying the D'Alambert's Principle for this case, the moment equilibrium equation can be determined:

$$\textstyle\sum_1 \mathbf{M} = M + mgQ\sin\phi = 0 \qquad (5)$$

Thus,

$$\phi = -\arcsin\frac{M}{mgQ} \tag{6}$$

Table 1 The characteristics of angle φ (degree)

M	φ
0	0
M < −mgQ	≥90 (always stable)
M >mgQ	<−ψ (always unstable)
|M| ≤ mgQ	−ψ≤φ≤90

As for rear edge (edge 1), assume that M = 0, the equilibrium plane coincides with vertical plane, and instantaneous orientation angle of equilibrium plane φ = 0. If increase M in left direction, the equilibrium plane moves toward the right, φ = −ψ represents a situation when the restoring moment is zero and the object is on the onset of instability. To guarantee the existence of the φ, as long as |M| ≤ mgQ, when M < −mgQ, the object is always stable, it means the object will never be unstable around the rear edge of support boundary. And when M > mgQ, the object is always unstable. Thus −ψ ≤ φ ≤ 90.

Extending this hypothesis for the Field Robot, depicted in Fig. 2, the vehicle is equipped a mobile manipulator operated by hydraulic system, the total moment at the equilibrium plane for rear edge, is obtained:

$$\sum M = M + \vec{F}\vec{R} + mg\left|\vec{Q}\right|\cos\gamma\sin\phi = 0 \tag{7}$$

The angle φ is calculated as:

$$\phi = \begin{cases} \max\left(-\sin^{-1}\left(\frac{M+\vec{F}\vec{R}}{mg\left|\vec{Q}\right|\cos\gamma}\right), -\psi+\alpha\right) \\ \quad \text{for} \left|M+\vec{F}\vec{R}\right| \le mg\left|\vec{Q}\right|\cos\gamma \\ 90 \\ \quad \text{for} \left|M+\vec{F}\vec{R}\right| > mg\left|\vec{Q}\right|\cos\gamma \end{cases} \tag{8}$$

Where, γ is the slope angle of current edge makes with the horizontal plane. The angle α is the slope angle of the tracks, make with the horizontal plane, it is the angle of inclined plane, this case is applied for the rear edge of support boundary.

So that, the instantaneous equilibrium plane of vehicle is subject to force and moment of manipulator, quality of the grounds. In the above equation, m is the mass of the tracked base; F and M are sum of forces and moments of mobile manipulator. By using the dynamic equation of manipulator, the net force and moment can be calculated using Newton-Euler dynamics methods.

2.3 Dynamics Equation of Motion

This part describes a model to determine the forces and moments when the Field Robot operates without external reaction. This method is to calculate the accelerations, velocities, forces, and moments of each component basing on the kinematics of robotics presented by Koivo et al [9].

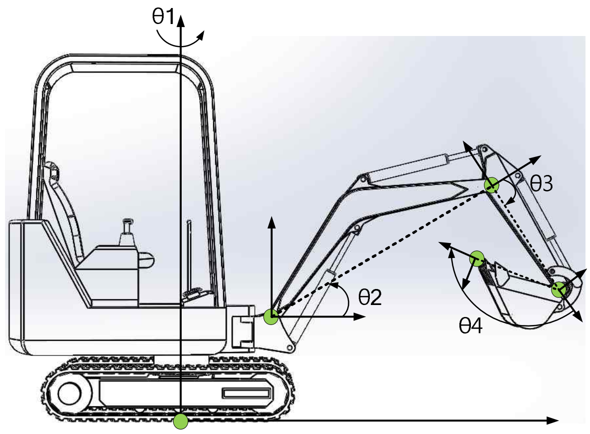

Fig. 4 Modeling of excavator S015

For modeling the impact energy of vehicle, the dynamic model of Field Robot is presented in general. The operating mechanism of Field Robot is identical a robotics of manipulator with four links respect to four rotation angles θ_1, θ_2, θ_3, θ_4 as in Fig. 4. In model of Koivo [9], the digging mode was considered. This model was extended by adding swing of basement. The dynamics equations are written for each component basing on the Newton-Euler dynamics method, Denavit-Hartenberg parameters, the rotational, translational velocities and accelerations for each component are showed in recursive forms as:

$$ {}^{i}\omega_i = R^{i}_{i-1}\,{}^{i-1}\omega_{i-1} + [0 \quad 0 \quad \dot{\theta}_i]^T \tag{9}$$

Where,

${}^{i}\omega_j$: the rotational velocity of component j in ith local coordinate frame.

R^{i}_{i-1} : the rotation matrix between two adjacent coordinate frame.

$\dot{\theta}_i$: the rotational velocity of component i relative to the previous component.

And then, the expression of rotational acceleration:

$$ {}^{i}\alpha_i = R^{i}_{i-1}\,{}^{i-1}\alpha_{i-1} + [0 \quad 0 \quad \ddot{\theta}_i]^T \tag{10}$$

Similarly, the translational velocity ${}^{i}\nu_i$ acceleration ${}^{i}a_i$ of component i in the ith coordinate frame

$$ {}^{i}v_i = R^{i}_{i-1}\,{}^{i-1}v_{i-1} + {}^{1}\omega_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{O_{i-1}}) \tag{11}$$

$$ \begin{aligned} {}^{i}a_i = {} & R^{i}_{i-1}\,{}^{i-1}a_{i-1} + {}^{i}\alpha_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{O_{i-1}}) \\ & + {}^{i}\omega_i \times \left({}^{i}\omega_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{O_{i-1}})\right) \end{aligned} \tag{12}$$

Where ${}^{i}\vec{p}_{O_j}$ is position vector of point O_j in the i^{th} coordinate frame.

Therefore, the translational velocity ${}^{i}\nu_{Gi}$ and acceleration ${}^{i}a_{Gi}$ of the gravity center G_i of component i are defined as follows:

$$ {}^{i}v_{Gi} = {}^{i}v_i + {}^{i}\omega_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{G_i}) \tag{13}$$

$$ \begin{aligned} {}^{i}a_{Gi} = {} & {}^{i}a_i + {}^{i}\alpha_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{G_i}) \\ & + {}^{i}\omega_i \times \left({}^{i}\omega_i \times ({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{G_i})\right) \end{aligned} \tag{14}$$

The inertial forces and moments that act on component i can be expressed in the i^{th} coordinate frame:

$$ {}^{i}F_{Oi} = m_i({}^{i}a_{Gi} + g_i) \tag{15}$$

$$ {}^{i}M_{Oi} = {}^{i}I^{i}_{O}\,{}^{i}\omega_i + {}^{i}\omega_i \times {}^{i}I^{i}_{O}\,{}^{i}\omega_i \tag{16}$$

Since the above results, the summation of forces and moments of manipulator is calculated recursive form by using the Newton-Euler method. In the local coordinate frame, the force ${}^{i}\vec{F}_{(i-1)i}$, and moment ${}^{i}\vec{M}_{(i-1)i}$ acting on component i from component (i-1) without external forces are expressed:

$$ {}^{i}\vec{F}_{(i-1)i} = {}^{i}R_{i+1}\,{}^{i}\vec{F}_{i(i+1)} + {}^{i}\vec{F}_{Oi} \tag{17}$$

$$ \begin{aligned} {}^{i}\vec{M}_{(i-1)i} = {} & {}^{i}\vec{M}_{0i} + {}^{i}R_{i+1}\,{}^{i+1}\vec{M}_{i(i+1)} \\ & +({}^{i}\vec{p}_{O_i} - {}^{i}\vec{p}_{O_{i-1}}) \times {}^{i}\vec{F}_{i(i+1)} \\ & +({}^{i}\vec{p}_{O_{i-1}} - {}^{i}\vec{p}_{G_i}) \times {}^{i}\vec{F}_{0i} \end{aligned} \tag{18}$$

The equations (17), (18) can be solved backward interpolation by starting from the end-effector and proceeding toward the base. So, the force and moment of manipulator acting on the basement could be calculated by this model.

The detail parameters are depicted in Fig. 5.

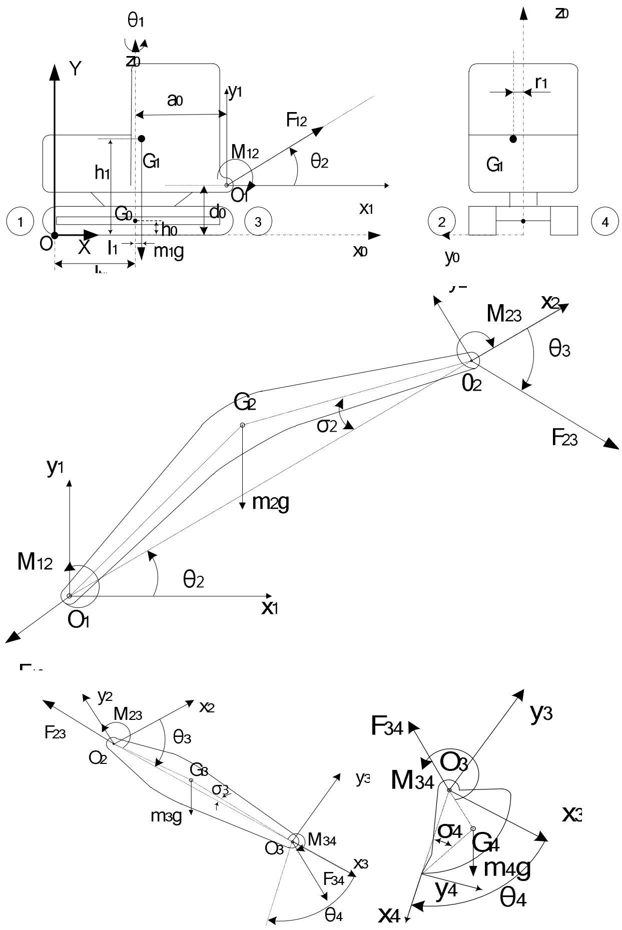

Fig. 5 Local coordinate system of sub-components.

Table 2 The parameters of excavator S015.

Parameters	Values (kg)	Parameters	Values (m)
m_{cabin}	1340	a_0	0.596
m_{boom}	42.865	d_0	0.66
m_{arm}	15.079	l_2	1.693
m_{bucket}	45	l_3	0.851
		l_4	0.478

3. Simulations

As known, the Energy Stability Level is a function:

$$ESL = f(F, M, \phi, \psi, \alpha, \gamma)$$

This simulation examines the stability of excavator basing on the concept of Energy Stability Level by using Matlab/Simulink program as Fig. 6.

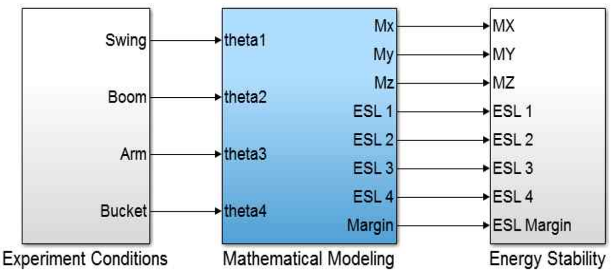

Fig. 6 Diagram of Matlab/Simulink program.

The experiment conditions and the terrain condition will be modeled in Mathematical Modeling for examining the effects of some different cases.

The simulation under effects swing motion and terrain conditions are carried out in four cases.

- Case 1: Effects of swing motion on planar.
- Case 2: Effect of attachments' configuration.
- Case 3: Effect of inclined terrain.
- Case 4: Excavator on 2 axes inclined terrain.

3.1 Case 1: Effects of swing motion on planar

In this research, we carried out the simulation effect of swing motion with the fixed posture is set with angles: $\theta_2 = 10^{\circ}$, $\theta_3 = -24.489^{\circ}$, $\theta_4 = 10.69^{\circ}$ shown in Fig. 7. The cabin is rotated one circle 360 degrees with velocity 30 deg/s as Fig. 9. And the locus of gravity center of excavator is depicted in Fig. 8.

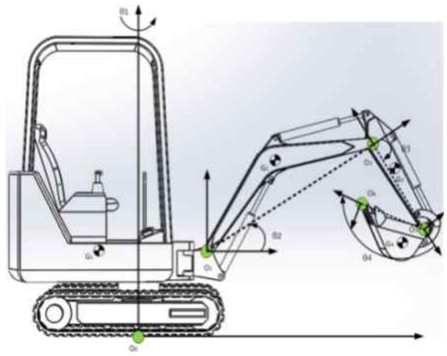

Fig. 7 Excavator swing with fixed posture of manipulator.

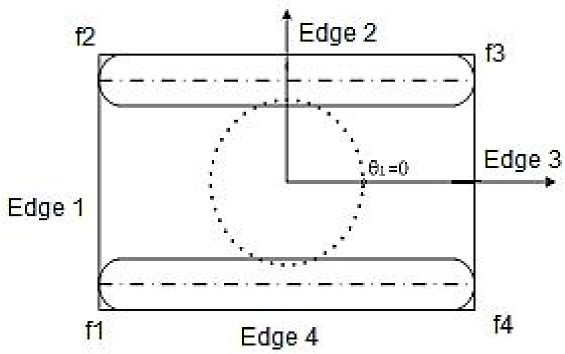

Fig. 8 Locus of Field Robot gravity center.

When the excavator is driven like that, the inertial moments at 3 axes (x axis, y axis, z axis) was modeled by motion equation is extended for all at origin coordinate frame from equation as in Fig. 10.

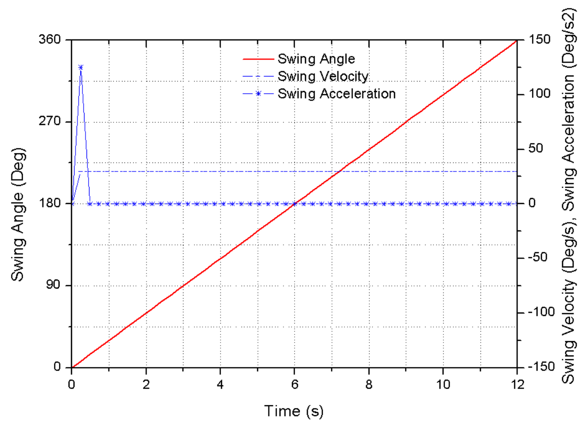

Fig. 9 Swing motion of cabin

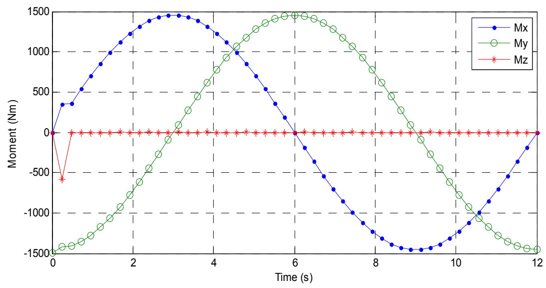

Fig. 10 Moments of 3 axesin origin coordinate.

The energy stability levels of 4 edges are depicted in Fig. 11 which shows out that the change of energy stability level following swing motion of cabin.

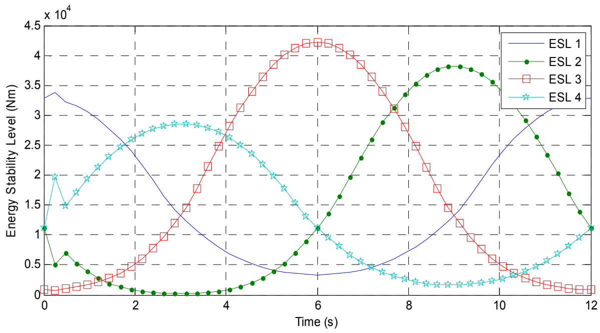

Fig. 11 Energy Stability Level of support boundary's edges.

The energy stability margin is the minimum value of all energy stability levels at instant time. The margin was obtained as in Fig. 12.

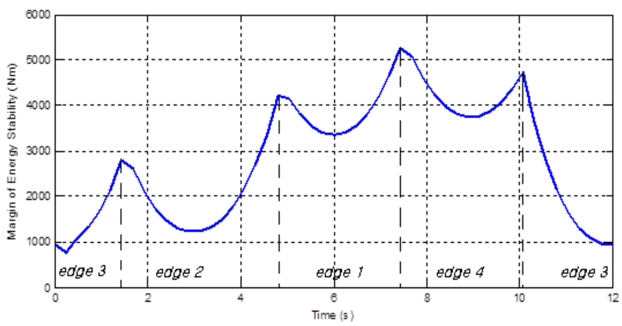

Fig. 12 Margin of energy stability

The margin of energy stability changed along with the edge of support boundary when the position of manipulator swings one circle. In this case, the stability of excavator is guaranteed following the definition of energy stability level in section 2.

3.2 Case 2: Effect of attachments' configuration

To evaluate effects of attachments' configuration, two configurations of attachments will be investigated as Fig. 13, in that the radius of gravity center is various. The margins of energy stability of two situations are shown as in Fig. 14. As known, the margin describes the stability level of machine. The margin of situation(a) is higher than situation (b), so situation (a) is more stable than situation (b).

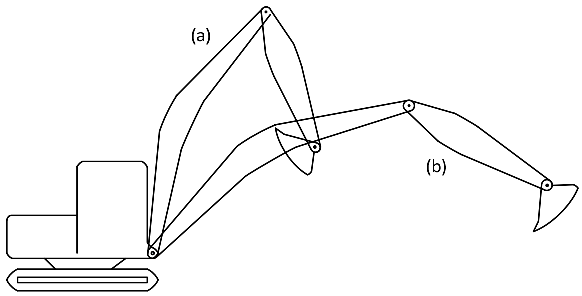

Fig. 13 Two configurations of attachments

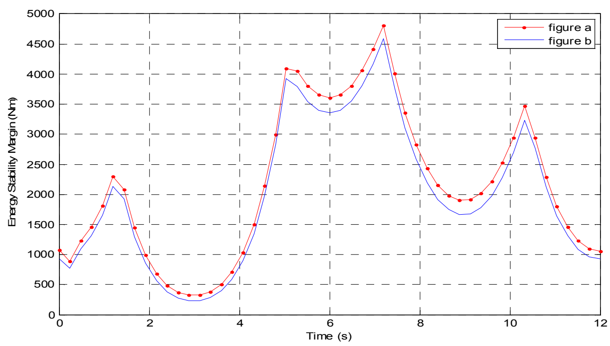

Fig. 14 Margin of energy stability

3.3 Case 3: Effect of inclined terrain

Fig. 15 depicts the Field Robot operates on the inclined terrain with slope angle α. The change of energy stability levels are compared to the case of planar terrain. The change occurred for rear edge and front edge. The stability level for rear edge (edge 1) decreased because it was on downhill side, and the stability level for front edge (edge 3) increased as in Fig. 16.

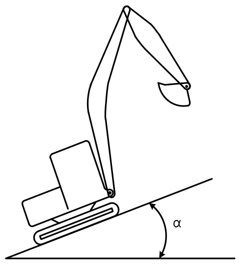

Fig. 15 Field Robot on inclined terrain

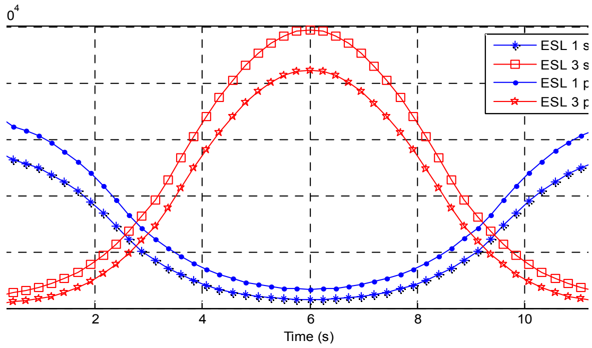

Fig. 16 Comparison of Energy Stability Levelat rear and front edges of support boundary.

3.4 Case 4: Field Robot on 2 axes inclined terrain

When the excavator operates on a rough terrain, so the excavator is seesawed along with the change of roll, pitch, yaw of 3 axes. We assume that the roll and pitch angles of excavator is changed, and use two angles α, γ randomly for describing this situation as in Fig. 17, 18, and the margin of energy stability is shown in Fig. 19.At the time between second 2 and second 4, the margin is small than zero. If the Field Robot operates on the terrain with identical rough condition, it will be turned over. In part 3.3, the longitudinal stability is considered, this simulation represents basically the effect of longitudinal and lateral stability condition to Field Robot operation.

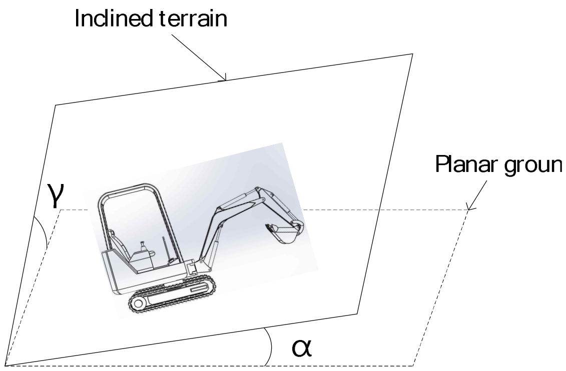

Fig. 17 Field Roboton 2 axes inclined terrain.

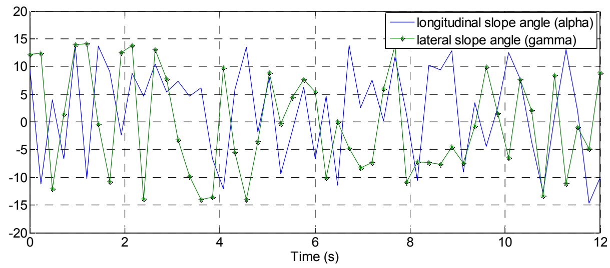

Fig. 18 The random slope angle values of 2 axes inclined terrain

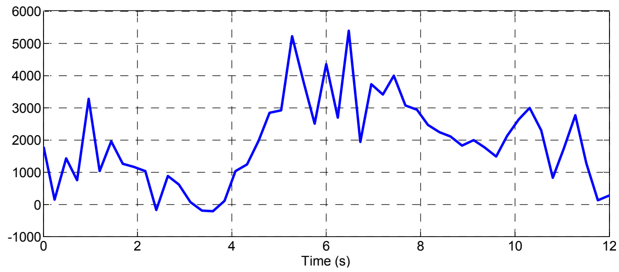

Fig. 19 Margin of energy stability

3.5 Simulation background

The stability of such Field Robot was estimated by method of energy, which is subject to concept of energy stability, including potential energy and kinetic energy.

The stability of excavator, studied by using the concept of energy stability level, is affected by:

- Swing motion.
- Radius of gravity center.
- Conditions of terrain.
- Dynamics of excavator.

Following these simulations, the radius of gravity center and condition of terrain most effect to change the stability level of excavator.

4. Conclusions

This research had investigated the stability of excavator using the Energy Stability Level Method under effects of swing motion, at particular postures of manipulator and terrain conditions.

This work uses computer-based program for estimating stability to supply useful predictions of stability analysis to designers and operators.

The stability of Field Robot is meaningful in heavy-duty industrial tasks. Moreover, the research of such stability plays an important role in automation applications and remote control.

Acknowledgements

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References

1) Robert B. McGhee, Geoffrey I. Iswandhi, “Adaptive locomotion of a multi-legged robot over rough terrain”, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 9, No. 4, pp. 176-182, 1979.

2) J. K. Davidson, G. Schweitzer, “A mechanics-based computer algorithm for displaying the margin of static stability in four-legged vehicles”, Transactions of ASME Journal of Mechanical Design, Vol. 112, No. 4, pp. 480-487, 1990.

3) Dominic A. Messuri, Charles A. Klein, “Automatic body regulation for maintaining stability of a legged vehicle during rough-terrain locomotion”, IEEE Transactions on Robotics and Automation, Vol. 1, No. 3, pp. 132-141, 1985.

4) G. Papadopoulos, D.A. Rey, “A New Measure of Tip over Stability Margin for Mobile Manipulator”, Proceedings of IEEE International Conference on Robotics and Automation, pp. 3111-3116, April 1996.

5) E. Garcia, P. Gonzalez de Santos, “A New Dynamic Energy Stability Margin for Walking Machines”. Proceedings of International Conference on Advanced Robotics, 2003 Portugal.

6) T. H. Lim, S. Y. Yang, “Development of Tipping-Over Rate Computation System for Hydraulic Excavator Having Crane Function”, Science and Technology KORUS 2004, Proceedings of the 8th Russian-Korean International Symposium, pp.76-79, 2004.

7) S. Sugano, Q. Huang, I. Kato, “Stability Criteria in Controlling Mobile Robotic System”, Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 832-838, Japan July 1993.

8) A. Ghasempoor, N. Sepehri, “A measure of stability for mobile manipulators with application to heavy-duty hydraulic machines”, Transactions of the ASME Journal of Dynamic System, Measurement, and Control, Vol. 120, No. 3, pp. 360-370, 1998.

9) A. J. Koivo, M. Thoma, E. Kocaoglan, and J. Andrade-Cetto, “Modeling and control of excavator dynamics during digging operation”, ASCE Journal of Aerospace Engineering, Vol. 9, No. 1, pp. 10-18, 1996.

10) ES. Tafazoli et al., “Parameter Estimation and Actuator Friction Analysis for a Mini Excavator”, Proceedings of IEEE International Conference on Robotics and Automation, pp.329-334, April 1996.

11) S. Dubowsky, E. E. Vance, “Planning mobile manipulator motions considering vehicle dynamic stability constraints”, Proceedings IEEE International Conference on Robotics and Automation, Scottsdale, AZ, Vol. 3, pp. 1271-1276, 1989.

12) Jesús Morales et al., “Center of Gravity Estimation and Control for a Field Mobile Robot with a Heavy Manipulator”, Proceedings of the 2009 IEEE International Conference on Mechatronics, Spain, April 2009.