Experimental and Theoretical Study on the Motion of ROV with Crawler system

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Abstract- Mobility characteristic of ROV with crawler system in steady running was theoretically and experimentally investigated. It was found experimentally that flipper type crawler system gave advantages when running on the irregular seafloor and when working on the seafloor. On the other hand, the experiment suggests that the static or quasi-static analysis is not enough to estimate the motion of ROV with a crawler system. This paper also shows theoretical approach on evaluating dynamic effects of the ROV motion. The crawler motion is formulated by the lumped-mass method. A computer code has been developed and some numerical results are shown.

I. INTRODUCTION

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has developed the ROV ABISMO (Automatic Bottom Inspection and Sampling Mobile) [1] as shown in Fig.1, which is capable of diving to the deepest sea and obtaining sediment samples from the sea floor. The ABISMO actually succeeded in dives deeper than 10,000m in the Marian Trench and recorded 10,257m dive. The ABISMO has, among its features, a crawler system in addition to thrusters as a mobility function when moving on the seabed [2]. However, further development was needed for ABISMO to move on the seafloor with the crawler system. And JAMSTEC has also started research and development activities for the next generation deep-sea exploration technology in which crawler system to observe on the sea floor is listed.

Figure 1. Picture of ABISMO.

In the previous studies, mobility characteristics in steady running were theoretically and experimentally investigated. It was found experimentally that a lightweight ROV is apt to run in wheelie in some cases in spite of the fact that the vehicle could run stably on land. In order to achieve adequate mobility of the crawler systems when running on the seafloor, an additional advanced mechanism is needed because the seafloor is irregular, bumpy or sloping terrain. There is a height limit of a bump to run or climb up. Generally the crawler cannot clime up a higher bump than a half of the diameter of a forward wheel of a crawler system. One of the solutions is to possess a function of a rotating mechanism on the crawler, which can rotate the crawler system itself, called flipper system. So a flipper type crawler system consisting of 4 crawlers and flipper system for each crawler to run on the irregular seafloor is proposed in this study. The flipper type crawler system gives an advantage not only when running on the irregular seafloor but also when working on the seafloor. It is important to keep the attitude of the ROV to prevent fall down especially when holding a heavy sample by a manipulator or being subjected to a reaction force of heavy duty. In this situation, flipper type crawler exercises the advantage because the crawler can be rolled out, then the lever become to be wide.

On the other hand, the theoretical work on the stable running condition of the ROV with a crawler system gave an idea of “stable area” for the center of gravity and the center of buoyancy. However, this theory is not enough to estimate the motion of ROV with a crawler system. Since the theory considered only static or quasi-static effects and dynamic effects on the crawler system were ignored. It is important to analyze motion dynamically for clarifying the running performance of the ROV with crawler system. This paper shows theoretical studies on evaluating dynamic effects of the ROV motion as well as the experimental study.

II. EXPERIMENTS

As we presented in the previous paper [3], we developed a small-size ROV with the flipper crawler systems, and conducted experiments in the water tank and on seafloor. The one of crawler system is shown in Fig.2.

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Figure 2. The ROV equipped with the dual-row flipper crawler system.

A. *Experiments of Running in a Water Tank*

Experiments were conducted in a water tank of JAMSTEC. A tilt table which angle can be changeable was set on the bottom of the water tank as shown in Fig.3.

Generally describing, the ROV with the flipper crawler systems could run on the tilt table with carpet having an angle of 30 degrees. During running on the block of logs, advantage of the flipper crawler system was obviously observed. The ROV with the flipper crawler systems could run over a log easily. However the ROV is slightly apt to run in wheelie in some cases when the ROV starts to run.

Figure 3. Running on the block of logs in the water tank.

B. *Experiments of Running on the Seafloor*

Experiments were conducted at the sea of less than 10m water depth to confirm the mobility of the crawler systems on the irregular seafloor. There were sand seafloor, inclined area and rock area with inclination.

The ROV with the flipper crawlers could run on the rock seafloor by operating the flipper mechanism. However the crawler system slipped in some cases, when the ROV with crawler system starts to run or to climb up bumps.

Figure 4. Running on the rock area at sea

C. *Results of Experiment*

The result of the experiments in the water tank and at sea shows advantage of the developed flipper type crawler to run and climb up the bumps and to keep the attitude of the ROV.

On the other hand, during the experiments, the following phenomena which would influence on running performance were observed.

1) The ROV with crawler system slipped in some cases when the ROV starts to run and starts to climb up.
2) The ROV with crawler system was apt to run in wheelie in some cases when the ROV starts to run.

The phenomena will not be clarified by previous research [4] which is a static or a quasi-static approach because it is supposed to be influenced by dynamic effects. Thus, the dynamic effects are needed to investigate, for example, the dynamic shearing force between the crawler belt and sand, the dynamic effect on the motor torque and so on.

III. DYNAMIC ANALYSIS

In this paper, the model as shown Fig.5 is analyzed. An ordinary type crawler is only analyzed for the sake of simplicity. The method can be extended to the flipper crawler system.

The coordinate system is shown in Fig.5 and Fig.6.

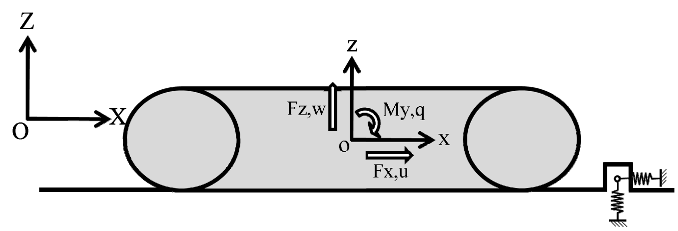

Figure 5. ROV model

A. *Governing Equation of Motions of Crawler Belt*

It is assumed that the Crawler belt is represented by a set of discrete masses interconnected by non-mass linear springs as illustrated in Fig.6. The external forces acting on a crawler belt are gravity, line tension, normal component of reaction, and external force to keep velocity.

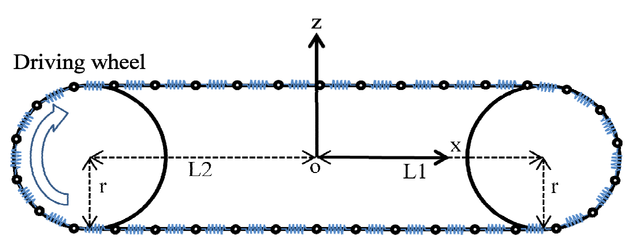

Figure 6. Crawler belt model

The governing equations of motion of i-th lumped mass are as follows;

$$m\ddot{x}_j = Fx_j \qquad (1)$$
$$m\ddot{z}_j = Fz_j \qquad (2)$$

m : Mass of j-th lump.

$\ddot{x}_j$, $\ddot{z}_j$: Acceleration of j-th lumped mass in x and z directions respectively.

The nodal components of external forces Fx_j and Fz_j in (1) and (2) can be written by

$$Fx_j = a_{xj} T_j + b_{xj} T_{j-1} + c_{xj} R_j + d_{xj} F_j + U_j \tag{3}$$

$$Fz_j = a_{zj} T_j + b_{zj} T_{j-1} + c_{zj} R_j + d_{zj} F_j + V_j \tag{4}$$

where

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- T_j : Tension in segment between j-th and (j+1)-th lumped mass.
- R_j : Normal component of reaction in j-th lumped mass.
- F_j : External force to keep velocity in j-th lumped mass.
- U_j, V_j : Gravity force in j-th lumped mass.
- $a_{xj}, b_{xj}, c_{xj}, d_{xj}$: Function of x_j, z_j
- $a_{zj}, b_{zj}, c_{zj}, d_{zj}$: Function of x_j, z_j

The additional constraint equations of the crawler belt are as follows;

Position constraint $(x \geq L1)$

$$(x_j - L1)^2 + y_j^2 = r^2 \tag{5}$$

Distance constraint

$$(x_j - x_{j+1})^2 + (z_j - z_{j+1})^2 = dL^2 (1 + T_j / A \cdot E) \tag{6}$$

Velocity constraint $(x \leq -L2)$

$$Vt = \sqrt{Vx_j^{\ 2} + Vz_j^{\ 2}} \tag{7}$$

- A : Crass-sectional area of Crawler belt
- E : Young's modulus of Crawler belt
- x_j, z_j : position of j-th lumped mass

B. *Solution of the Problem*

The governing equations (3) and (4) can be reduced to

$$\ddot{x}_j = (a'_{xj} T_j + b'_{xj} T_{j-1} + c'_{xj} R_j + d'_{xj} F_j + U'_j) / \Delta t^2 , \tag{8}$$

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$$\ddot{z}_j = (a'_{zj} T_j + b'_{zj} T_{j-1} + c'_{zj} R_j + d'_{zj} F_j + V'_j) / \Delta t^2 . \tag{9}$$

On the other hand, the nodal accelerations and velocities of the next step ($\ddot{x}_j^{n+1}, \ddot{z}_j^{n+1}$) , ($\dot{x}_j^{n+1}, \dot{z}_j^{n+1}$) can be expressed by the following finite difference equation which is called the Houbolt Method.[5]

$$\ddot{s}_j^{n+1} = (2 s_j^{n+1} - 5 s_j^n + 4 s_j^{n-1} - s_j^{n-2}) / \Delta t^2 \tag{10}$$

$$\dot{s}_j^{n+1} = (11 s_j^{n+1} - 18 s_j^n + 9 s_j^{n-1} - 2 s_j^{n-2}) / 6 \Delta t \tag{11}$$

where a dot over s_j denotes time differentiation and s_j in (10) and (11) represents x_j or z_j .

Combining equations (8), (9), and (10), the nodal displacements x_j^{n+1} and z_j^{n+1} of next time step n+1 are derived as follows:

$$\begin{aligned} x_j^{n+1} &= 5/2\, x_j^n - 2\, x_j^{n-1} + 1/2\, x_j^{n-2} \\ &\quad + (a'^{n+1}_{xj} T_j^{n+1} + b'^{n+1}_{xj} T_{j-1}^{n+1} + c'^{n+1}_{xj} R_j^{n+1} \\ &\qquad + d'^{n+1}_{xj} F_j^{n+1} + U'_j) / 2 \end{aligned} \tag{12}$$

$$\begin{aligned} z_j^{n+1} &= 5/2\, z_j^n - 2\, z_j^{n-1} + 1/2\, z_j^{n-2} \\ &\quad + (a'^{n+1}_{zj} T_j^{n+1} + b'^{n+1}_{zj} T_{j-1}^{n+1} + c'^{n+1}_{zj} R_j^{n+1} \\ &\qquad + d'^{n+1}_{xj} F_j^{n+1} + U'_j) / 2 \end{aligned} \tag{13}$$

To obtain the external forces of next time step T_j^{n+1} , R_j^{n+1} , F_j^{n+1} , the Newton-Raphson Method is used. It is assumed that T_j^{n+1} , R_j^{n+1} , F_j^{n+1} consists of two components as follows;

$$T_j^{n+1} = \tilde{T}_j^{n+1} + \Delta T_j^{n+1} \tag{14}$$

$$R_j^{n+1} = \tilde{R}_j^{n+1} + \Delta R_j^{n+1} \tag{15}$$

$$F_j^{n+1} = \tilde{F}_j^{n+1} + \Delta F_j^{n+1} \tag{16}$$

where $\tilde{T}_j^{n+1}$, $\tilde{R}_j^{n+1}$, $\tilde{F}_j^{n+1}$ are the tentative value and ΔT_j^{n+1} , ΔR_j^{n+1} , ΔF_j^{n+1} are the correction.

In this study, the following equations are defined that are functions of crawler belt tension, normal component of reaction, and external forces to keep velocity of next step. These equation are derived from (5), (6), and (7).

$$\begin{aligned} \Psi p_j^{n+1} &= (x_j^{n+1} - L1)^2 + y_j^{n+1\,2} - r^2 \\ &= \Psi p_j^{n+1} (T_{j-1}^{n+1}, T_j^{n+1}, R_j^{n+1}, F_j^{n+1}) = 0 \end{aligned} \tag{17}$$

$$\begin{aligned} \Psi d_j^{n+1} &= (x_j^{n+1} - x_{j+1}^{n+1})^2 + (z_j^{n+1} - z_{j+1}^{n+1})^2 \\ &\qquad - dL^2 (1 + T_j^{n+1} / A \cdot E) \\ &= \Psi d_j^{n+1} (T_{j-1}^{n+1}, T_j^{n+1}, T_{j+1}^{n+1}, R_j^{n+1}, R_{j+1}^{n+1}, F_j^{n+1}, F_{j+1}^{n+1}) = 0 \end{aligned} \tag{18}$$

$$\begin{aligned} \Psi v_j^{n+1} &= Vt - \sqrt{Vx_j^{n+1\,2} + Vz_j^{n+1\,2}} \\ &= \Psi v_j^{n+1} (T_{j-1}^{n+1}, T_j^{n+1}, T_{j+1}^{n+1}, R_j^{n+1}, R_{j+1}^{n+1}, F_j^{n+1}, F_{j+1}^{n+1}) = 0 \end{aligned} \tag{19}$$

Expanding Ψp_j^{n+1} in a Taylor series about the $\left(\tilde{T}_{j-1}^{n+1}, \tilde{T}_j^{n+1}, \tilde{R}_j^{n+1}, \tilde{F}_j^{n+1}\right)$, thus the following equation is obtained.

$$\begin{aligned} \Psi p_j^{n+1} &= \tilde{\Psi} p_j^{n+1} + \partial \tilde{\Psi} p_j^{n+1} / \partial T_{j-1}^{n+1} \cdot \Delta T_{j-1}^{n+1} \\ &\quad + \partial \tilde{\Psi} p_j^{n+1} / \partial T_j^{n+1} \cdot \Delta T_j^{n+1} + \partial \tilde{\Psi} p_j^{n+1} / \partial R_j^{n+1} \cdot \Delta R_j^{n+1} \\ &\quad + \partial \tilde{\Psi} p_j^{n+1} / \partial F_j^{n+1} \cdot \Delta F_j^{n+1} \\ &\quad + (\text{Higher oder terms}) = 0 \end{aligned} \tag{20}$$

Provided that the tentative values $\tilde{T}_j^{n+1}$, $\tilde{R}_j^{n+1}$ and $\tilde{F}_j^{n+1}$ are sufficiently close to the correct values T_j^{n+1} , R_j^{n+1} and F_j^{n+1} , the higher order terms in (20) are neglected , and thereby obtain a system of N linear equations for the differential correction ΔT_j^{n+1}, ΔR_j^{n+1} and ΔF_j^{n+1}.

$$\begin{aligned}-\tilde{\Psi}p_j^{n+1} &= \partial\tilde{\Psi}p_j^{n+1}/\partial T_{j-1}^{n+1}\cdot\Delta T_{j-1}^{n+1} \\ &+\partial\tilde{\Psi}p_j^{n+1}/\partial T_j^{n+1}\cdot\Delta T_j^{n+1}+\partial\tilde{\Psi}p_j^{n+1}/\partial R_j^{n+1}\cdot\Delta R_j^{n+1} \\ &+\partial\tilde{\Psi}p_j^{n+1}/\partial F_j^{n+1}\cdot\Delta F_j^{n+1}\end{aligned} \tag{21}$$

Calculation external forces of next step T_j^{n+1}, R_j^{n+1} and F_j^{n+1} by iteration. Then, the corrections ΔT_j^{n+1}, ΔR_j^{n+1} and ΔF_j^{n+1} are determined by (21).

Ψd_j^{n+1} and Ψv_j^{n+1} are expanded as follow (20), and (21).

C. *Governing Equation of Motions of ROV*

Motions of ROV are expressed by

$$\begin{bmatrix} M+A_{11} & 0 & 0 \\ 0 & M+A_{33} & -A_{53} \\ 0 & A_{53} & I_{yy}+A_{55}\end{bmatrix}\cdot\begin{bmatrix}\dot{u}\\ \dot{w}\\ \dot{q}\end{bmatrix}=\begin{bmatrix}F_{XR}\\ F_{ZR}\\ M_{YR}\end{bmatrix} \tag{22}$$

where

$$\begin{aligned}F_{XR} &= -(M+A_{33})\cdot q\cdot w - A_{35}\cdot q^2 \\ &+(M-\rho\nabla)\cdot g\cdot \sin\theta + X_{uu}u^2 + X_{ww}w^2 + F_{GX}\end{aligned} \tag{23}$$

$$\begin{aligned}F_{ZR} &= (M+A_{11})\cdot q\cdot w-(M-\rho\nabla)\cdot g\cdot\cos\theta \\ &+Z_{ww}w^2+Z_{qq}q^2+Z_w w+F_{GZ}\end{aligned} \tag{24}$$

$$\begin{aligned}M_{YR} &= A_{35}\cdot q\cdot u-(A_{11}-A_{33})\cdot u\cdot w \\ &+M_w w^2+M_{ww}w^2+M_{qq}q^2+T_{GY}\end{aligned} \tag{25}$$

A_{ij}	:Added mass for i-th mode due to jth mode motion
F_{XR}, F_{ZR}	: Friction of Ground.
T_{GY}	: Rotating torque
u, v, w	: Velocity component of ROV in –x, -y, -z, direction
q	: Angler velocity of ROV
M	: Mass of ROV
Z_{qq}, M_{qq}	: Hydrodynamic derivative of ROV with respect to angler velocity
X_{uu}, X_{ww}, Z_{ww}, Z_w, M_w, M_{ww}	: Hydrodynamic derivatives of ROV with respect to velocity
θ	:Eulerian angle[6]
ρ	: Water density
∇	: displacement

These equations are solved by the same method of crawler belt.

D. *Theoretical results*

Examples of numerical result are shown in Fig.7 and Fig.8. Fig.7 shows time history of driving-wheel torque when the crawler is accelerated. Experimental value and numerical value are normalized by each maximum value, because the electric current of the crawler drive motor was only measured. Comparing the predicted time history with those measured in the experiments of motor torque, the predicted tendency agrees well with measured one.

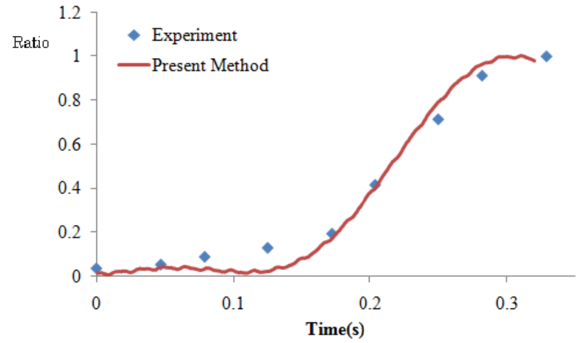

Figure 7. Torque of driving wheel.

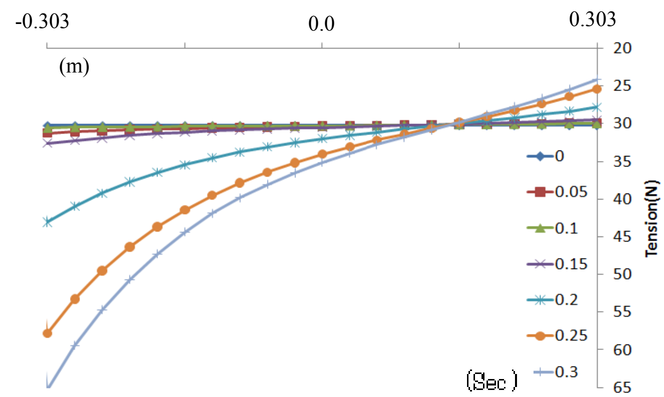

Figure 8. Time variation of the Tension distribution at the lower part of crawler.

Fig.8 shows the time variation of tension distribution when the crawler is accelerated.

IV. Conclusions

We conducted experiments in the water tank and at sea. The flipper crawler enables to run over higher obstacle.

We pay attention to some problems of running performance which could not understand by using a static analysis. So we show theoretical approach on evaluation of dynamic effects of the ROV motion. The crawler motion is formulated by the lumped-mass method. A computer code has been developed and some numerical results are shown. Results show the dynamic effect of the ROV with crawler system.

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