Experimental Research on Movability Characteristic of Crawler Driven ROV

Tomoya Inoue
JAMSTEC (Japan Agency for Marine-Earth Science and Technology)
Yokosuka, 237-0061 Japan

Tokihiro Katsui
Osaka Prefecture University
Sakai, 599-8531 Japan

Junichiro Tahara, Kazuaki Itoh, Hiroshi Yoshida, Shojiro Ishibashi, Ken Takagi
JAMSTEC (Japan Agency for Marine-Earth Science and Technology)
Yokosuka, 237-0061 Japan

***Abstract-* In order to reduce a tension on a cable, a deep sea ROV is designed to minimize the weight. However, such a light weight will influence on the movability of crawlers. As an initial investigation experiments were conducted in a water tank using a vehicle of ROV "ABISMO" changing the weight, the buoyancy, the center of gravity and the center of buoyancy. It was observed that the ROV ran unstably in some cases in spite of the fact that the ROV could run stably on land. Especially when the weight in water of was less, the stability of the ROV got worse. It seemed that the ROV could not run on the sea floor in such cases. On the other hand, the ROV ran stably when the ROV had an adequate weight in water and adequate center of gravity as well as center of buoyancy. This paper describes the experiment results of motion of the ROV running in water by means of crawler system. This paper also describes a fundamental theoretical investigation for ROV running in water. A discrimination chart of stable running is presented for the center of gravity and the center of buoyancy. The discrimination line is obtained with the weight and the buoyancy of ROV, the water residence, the point of its application and the dimension of crawlers.**

I. INTRODUCTION

Japan Agency Marine-Earth Science and Technology (JAMSTEC) has developed the ROV "ABISMO" (Automatic Bottom Inspection and Sampling Mobile) [1] [2] [3] being capable of diving to the deepest sea and obtaining sediment samples from the sea floor. ABISMO consists of a launcher and a vehicle which launches from the launcher to survey the sea floor. One of the features of ABISMO is to have crawler system in addition to thrusters as a mobility function.

ABISMO is lowered and hung by means of a cable from a vessel. In deep sea operation, a tension on the cable becomes greater and the cable will be damaged in extreme case. So, from the viewpoint of reducing the tension, a deep sea ROV is generally desired to reduce the weight in water. Actually the vehicle of ABISMO was designed so that the weight in water became less than 100kg. However, such a light weight will influence on the movability characteristic of crawler system. So, it is necessary to research the influence of the weight on the movability characteristic of crawler system in order to possess adequate movability on the sea floor. There are also other parameters such as the center of gravity, the center of buoyancy and the water resistance which will influence on the movability characteristic. These should be investigated as well.

As an initial investigation we conducted experiments using the vehicle of ABISMO in a water tank to observe the movability of crawler system in water. The experiments were conducted changing the weight and the buoyancy as well as the center of gravity and the center of buoyancy. In the experiments unstable running such as wheelie run was observed in some cases in spite of the fact that the vehicle could run stably on land. So it is important to establish fundamental theory of movability of crawler system in water.

The experiments using a model were also conducted to assess possibility to conduct the further experiments using the model because the parameters such as the buoyancy and the weight as well as the centers of buoyancy and gravity are easily changed.

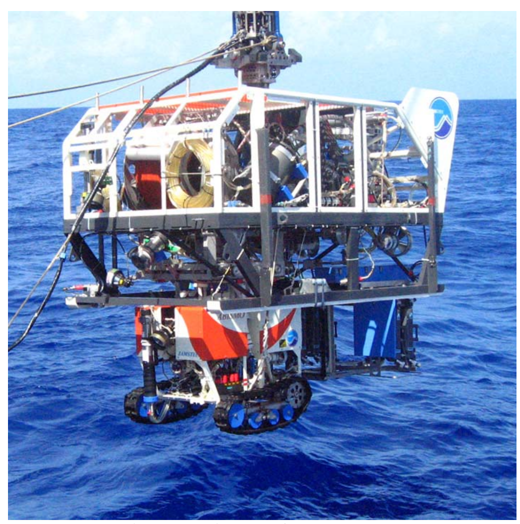

Figure 1. Picture of ABISMO.

978-1-4244-2620-1/08/$25.00 ©2008 IEEE

II. Fundamental Theory of Stable Running of Crawler System in Water

A. Equilibrium in Static Condition

The ROV in static condition is subjected to the gravity force W, the buoyant force B and a normal force N due to a ground reaction as shown in Fig. 2.

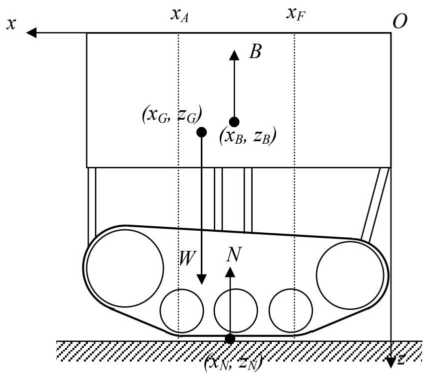

Figure 2. Static condition of ROV (vehicle) underwater.

The ROV may incline a little because x-coordinates of the application points of the gravity force and the buoyant force will not be in agreement. Then, ground pressure distribution P_s is obtained according to sinkage displacement z_s by Bekker's equation [5] using a sinkage exponent K_s and a sinkage coefficient n which are decided depending on the property of soils.

$$P_s(x) = K_s z_s(x)^n \tag{1}$$

However, in this paper the normal force N is assumed to be presented as a concentrated force. Also it is assumed that crawler belts will not be flexible. The point of application of the normal force x_N is obtained by equation (2) from vertical and horizontal equilibrium equations and moment equilibrium.

$$x_N = \frac{Wx_G - Bx_B}{W - B} \tag{2}$$

And it is required to satisfy the following equation in order for the ROV not to fall down in static condition.

$$x_F < \frac{Wx_G - Bx_B}{W - B} < x_A \tag{3}$$

B. Dynamic Model in Stable Running Condition

Consider the ROV in stable running. The ROV is subjected to a resistance force R_W and a shear force T in addition to W, B and N as shown in Fig. 3.

The point of application of the normal force is obtained by the following equation derived from vertical and horizontal equilibrium equations and moment equilibrium.

$$x_N = \frac{Wx_G - Bx_B + R_W(z_N - z_R)}{W - B} \tag{4}$$

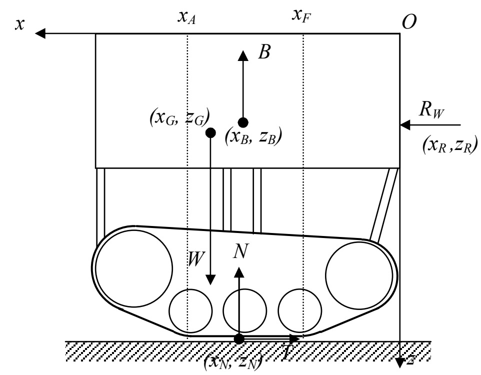

Figure 3. Stable running condition of ROV(vehicle) underwater.

Since the equation (3) is satisfied in static condition, $x_N<x_A$ is required for stable running. Then, it is required to satisfy the equation (5) in order for the vehicle not to fall down but to stably run.

$$x_G < \frac{B}{W}x_B + \frac{W - B}{W}x_A - \frac{R_W}{W}(z_N - z_R) \tag{5}$$

III. Experiments Using the Vehicle of ABISMO

A. Schematic Diagram of Experiment Using the Vehicle of ABISMO

Experiments using the vehicle of ABISMO were conducted in a water tank of JAMSTEC to observe its movability in water. Fig.4 shows the picture of the vehicle. Some equipment such as a light, a camera and hydrophone were not installed at the time of conducting the experiments. Fig. 5 shows the vehicle running in the water tank. The dimensions of the water tank are 40 m in length, 4 m in width and 2 m in depth. The motion of the vehicle in the water tank was observed from above as shown in Fig. 5 and also from observation windows provided in a side wall as shown in Fig. 6.

The ABISMO operation console could not be used for the experiments. So, stand-alone control device for the vehicle was newly developed for the experiments. The rotation of the crawler motors can be easily changed by using it for further experiments.

The experiments were conducted for the following 4 cases. The experiments of running forward and also backward were conducted several times for each case. In the experiments the dimensions of the crawler system such as a span of rollers and the torque of motors which actuates the rollers of the crawler system were fixed.

- Exp-1: Normal condition (actual condition)
- Exp-2: Blocks of buoyancy materials were put on the afterpart of the vehicle.
- Exp-3: Additional blocks of buoyancy material were put on the afterpart of the vehicle.
- Exp-4: Weight was put on the forepart of the vehicle.

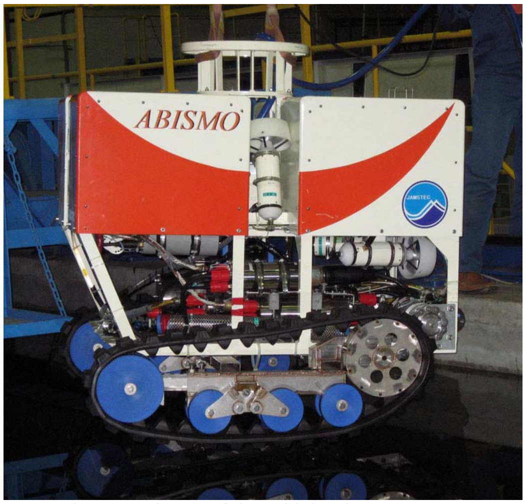

Figure 4. Picture of the vehicle of ABISMO.

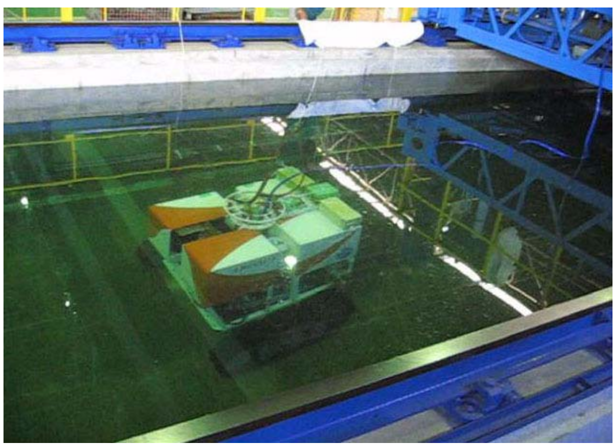

Figure 5. Picture of the vehicle running in the water tank.

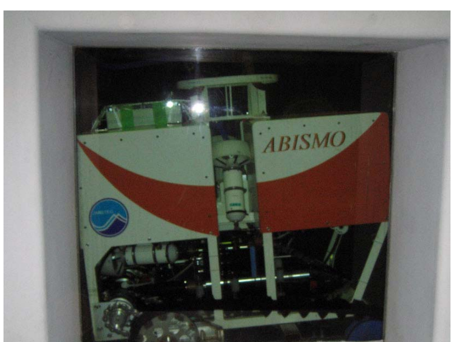

Figure 6. Picture of the vehicle running in the water tank from the observation window

B. Resistance Measurement Test

According to equation (5), water resistance R_W and the point of its application (0, z_R) are parameters of the stable running characteristics. So, resistance measurement test was conducted in the tank of Osaka University using the vehicle of ABISMO. The results are shown in Table 2 and Table 3.

TABLE 2
WATER RESISTANCE ON THE VEHICLE WHEN TOWING FORWARD

Velocity (m/s)	Resistance* (kgf)	Pitch moment* (kgf-m)	z-coordinate of the appl. point of resistance** (m)
0.086	0.49	0.51	0.320
0.188	1.64	1.84	0.399
0.285	3.60	4.10	0.422
0.386	6.49	7.47	0.434
0.486	10.26	11.78	0.430

* excluding the effect of a cylindrical strad used in the test
** the length from the center of the cell to the top to the vehicle is 0.718m

TABLE 3
WATER RESISTANCE ON THE VEHICLE WHEN TOWING BACKWARD

Velocity (m/s)	Resistance* (kgf)	Pitch moment* (kgf-m)	z-coordinate of the appl. point of resistance** (m)
0.097	0.52	0.59	0.427
0.193	1.82	1.99	0.379
0.293	3.81	4.21	0.387
0.390	6.56	7.23	0.384
0.488	9.96	10.98	0.384

* excluding the effect of a cylindrical strad used in the test
** the length from the center of the cell to the top to the vehicle is 0.718m

C. Stable Running Characteristics

The center of gravity and the center of buoyancy of the vehicle were estimated by hanging at two points, P1(x_1, 0) and P2(x_2, 0), on the top of the vehicle which is x-axis in Fig. 3. In the estimation, P1 and P2 were required to satisfy $x_2 > x_G > x_1$. Let θ_1 and θ_2 denote the angles between the line of action of gravity and the top cover of the vehicle when being hung at P1 and P2 in air respectively, also θ_1' and θ_2' the angles when being hung at P1 and P2 in water respectively, then the center of gravity and the center of buoyancy are obtained by equations (6)-(11).

$$x_G = \frac{x_1 \tan\theta_1 + x_2 \tan\theta_2}{\tan\theta_1 + \tan\theta_2} \tag{6}$$

$$z_G = \frac{(x_2 - x_1)\tan\theta_1 \tan\theta_2}{\tan\theta_1 + \tan\theta_2} \tag{7}$$

$$x_B = x_2 - \frac{W}{B}(x_2 - x_G) \tag{8}$$

$$z_B = (x_2 - x_1 - C_2 - C_1)\tan\theta_1' \tag{9}$$

$$C_1 = \frac{W}{B}(x_G - x_1 - \frac{z_G}{\tan\theta_1'}) \tag{10}$$

$$C_2 = \frac{W}{B}(x_2 - x_G - \frac{z_G}{\tan\theta_2'}) \tag{11}$$

The weight in air equivalent to the gravity force W and the buoyancy B as well as x-coordinates of the center of gravity x_G and the center of the buoyancy x_B are shown in table 4 for all 4 cases.

TABLE 4
WEIGHT, BUOYANCY AND THE CENTERS OF GRAVITY AND BUOYANCY OF THE VEHICLE IN EXPERIMENTS

No.	Weight in air (kgf)	Buoyancy (kgf)	x-coord. of the center of gravity (m)	x-coord. of the center of buoyancy (m)
Exp-1	318	226	0.680	0.635
Exp-2	322	236	0.686	0.659
Exp-3	331	253	0.706	0.709
Exp-4	351	256	0.671	0.702

The vehicle running in the water tank was recorded by a video camera from the observation windows. The velocity is estimated to have been 0.331 m/s by using the records. Substituting the above mentioned data into equation (5), the discrimination charts of stable running for 4 cases are obtained as shown in Fig. 7. The x-coordinates of the center of gravity and the center of buoyancy in the experiments are also plotted in Fig. 7.

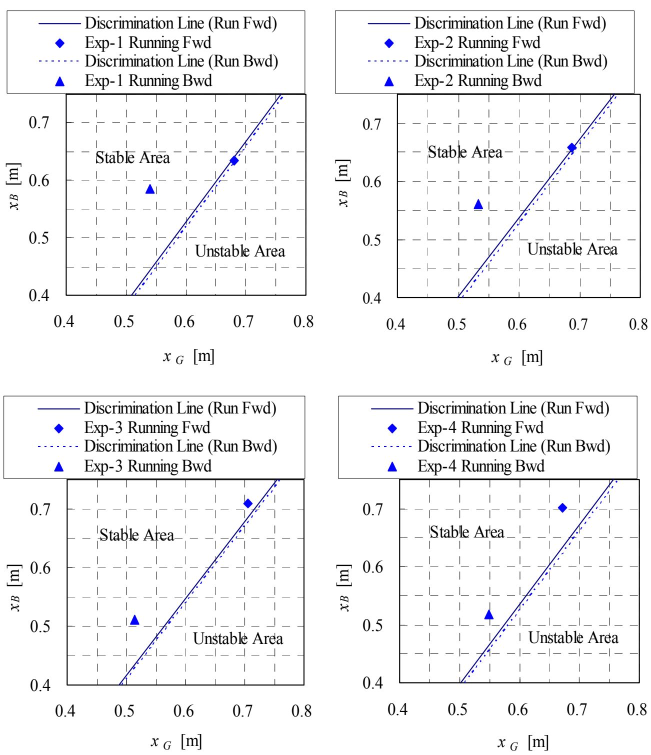

Figure 7. Discrimination charts of stable running and experiment conditions.

D. Observation in the Experiments

It was observed in some cases that the vehicle became or was apt to wheelie run when starting running. Actually, in the experiments of running forward in Exp-1 condition, the vehicle became wheelie when starting running and ran in wheelie as shown in Fig. 8. In this case, the aft part of frame structure rubbed with the bottom floor. This means that the vehicle might incline further and fall down if there had not been the frame. On the other hand, in the experiments of running backward in Exp-1 condition, the vehicle ran stably with keeping horizontally even posture as shown in Fig. 9. However, when stopping running, the vehicle was apt to front wheelie due to inertia. Focusing while running, it is said that the vehicle was not in stable running when running forward. On the other hand, the vehicle was in stable running when running backward. The observation agrees with the discriminant shown in Fig. 7. Although the frame did not rub with the floor in the experiments of running forward in Exp-2 condition, generally the same phenomena were observed.

According to Fig.7 increasing the x-coordinate of the center of buoyancy or decreasing the x-coordinate of the center of gravity improves the stable running characteristics. So, further buoyancy material was put on the aft (Exp-3) and the weight was put on the forward (Exp-4) to confirm the hypothesis.

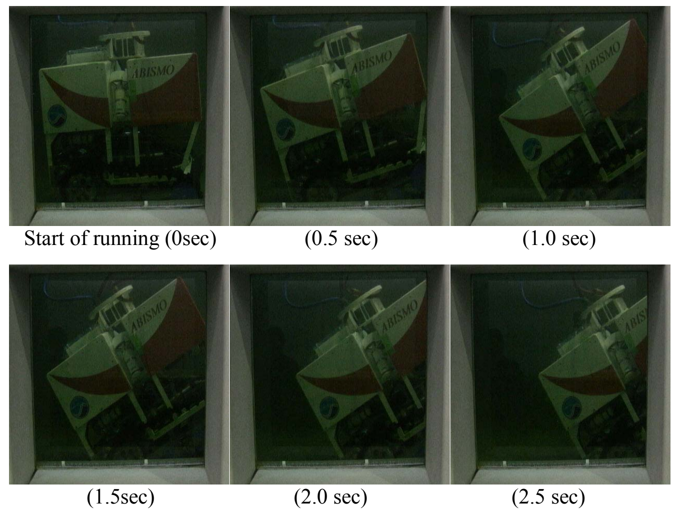

Figure 8. Pictures of the vehicle running forward (Exp-1).

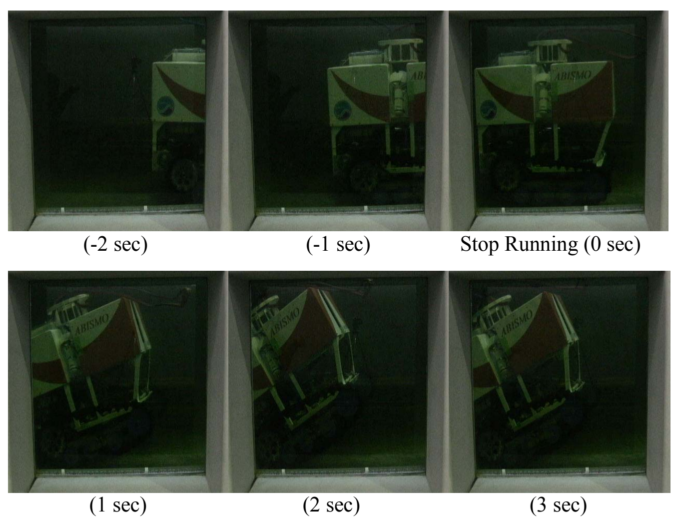

Figure 9. Pictures of the vehicle running backward (Exp-1).

In the experiments of running forward in Exp-3 condition, the vehicle was apt to wheelie when starting running, but the vehicle got back soon and ran stably as shown in Fig. 10. However, in the experiments of running backward in Exp-3 condition, the vehicle became wheelie when starting running and ran in wheelie as shown in Fig. 11. Focusing while running it is said that the vehicle was in stable running when running forward. It also seems that the vehicle was not in stable running in spite of the fact that the vehicle should be in stable running in this condition according to Fig.7. However, it cannot conclude because the vehicle was not inclined further after starting running. The same phenomena were observed in Exp-4 condition.

It is necessary to perform the further investigation on the motion of the ROV driven by means of the crawler system in water especially when starting running. Also it is necessary to investigate the stability in wheelie run to prevent the vehicle from falling down.

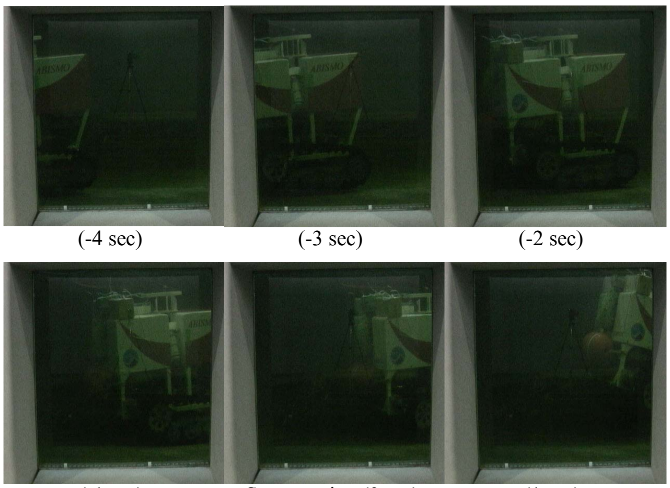

Figure 10. Pictures of the vehicle running forward (Exp-3).

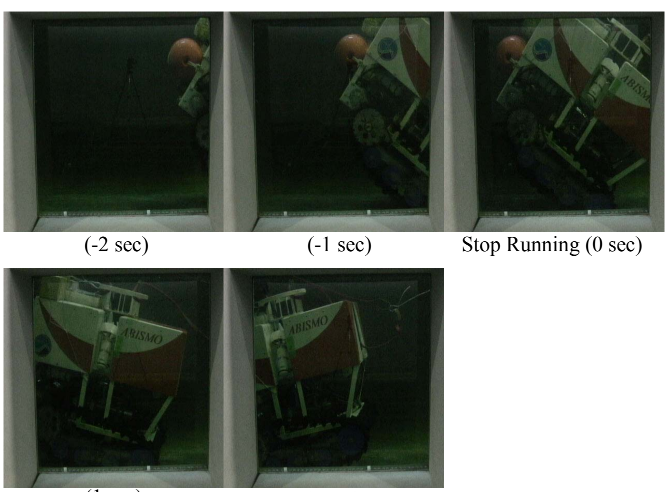

Figure 11. Pictures of the vehicle running backward (Exp-3).

IV. Experiments Using a Model

A. Schematic Diagram of Experiment Using a Model

It is difficult to change the weight and the buoyancy as well as the center of the gravity and the center of the buoyancy for the actual vehicle of ABISMO. So, we conducted the experiment using 1/8 model shown in Fig. 12 to observe if the same phenomena occurred and also to assess possibility to conduct the further experiments using the model.

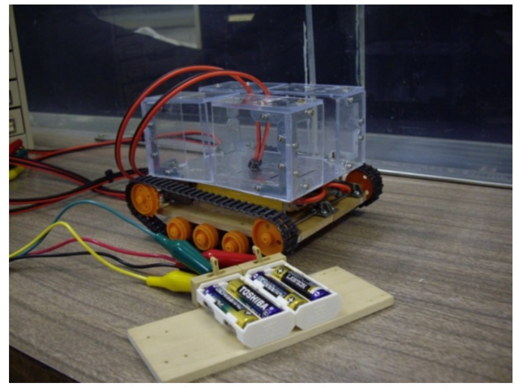

Figure 12. Picture of the 1/8 scale model of the vehicle of ABISMO.

TABLE 5
Weight and Dimensions of the Vehicle of ABISMO and the Model

Dimensions	Vehicle of ABISMO	Model
Lenght	1.220 m	0.155 m
Breadth	1.300 m	0.155 m
Height	1.025 m*	0.120 m
Weight in air	318 kgf**	570 gf
Buoyancy	226 kgf**	430 gf

* without a ring structure fit on the top

** at the time of conducting experiments (normal condition)

In the experiments it was observed that the vehicle became wheelie when starting running as well. So, after the crawlers stably ran, the model was gotten down onto the bottom floor and then it was released to run. It enabled evaluating stable running characteristics. The experiments were conducted changing the center of the gravity and also the center of buoyancy to find the points on the discrimination line of stable running.

The results are shown in Table 6. The resistance measurement test had not been conducted for the model. So, using the result of Exp-1, $R_W(z_N\text{-}z_R)$ was estimated by satisfying the following equation.

$$x_G = \frac{B}{W}x_B + \frac{W-B}{W}x_A - \frac{R_W}{W}(z_N - z_R) \tag{5}$$

Fig.13 shows the discrimination chart of stable running using it. The points on the discrimination line obtained from the experiments are also plotted in Fig.13. According to the results, it is said that the model can be used for further experiment to evaluate the stable running characteristics.

TABLE 6
THE EXPERIMENT RESULTS - THE POINTS ON THE DISCRIMINATION LINE OF STABLE RUNNING OBTAINED USING THE MODEL

	x_G	x_B	x_A
Exp-1	65.04	57.49	105.0
Exp-2	67.03	61.47	105.0
Exp-3	71.32	65.80	105.0

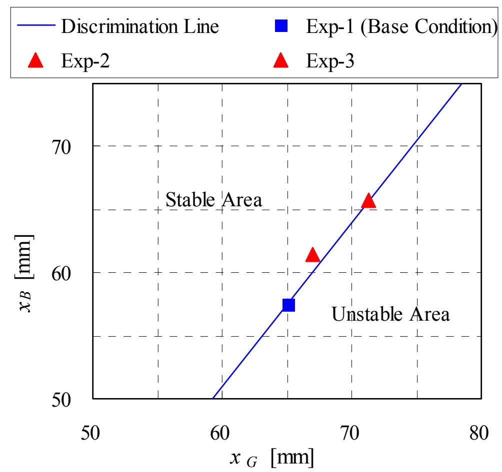

Figure 13. Discrimination chart of stable running and experiment conditions.

V. CONCLUSION

The experiments were conducted using the actual vehicle of ABISMO changing the weight and the buoyancy as well as the center of gravity and the center of buoyancy to observe the movability characteristics of the crawler system in water. In the experiments, unstable run such as wheelie run was observed in some cases especially when starting running in spite of the fact that the vehicle could run stably without wheelie on land. This means that the effect of water causing the water residence and the buoyancy influence on the stable running characteristics. Actually it is found that the gravity and the buoyancy as well as the center of gravity and the center of buoyancy will influence on the movability characteristics according to the results of the experiments.

Fundamental theory for stable running was presented. It gives the discrimination chart of stable running for the center of gravity and the center of buoyancy. The discrimination line is obtained with the weight and the buoyancy of the ROV, the residence and the point of its application and also dimensions of crawlers. However, it could not express the movability characteristics during acceleration. So, it is necessary to establish fundamental theory of the motion of the ROV driven by means of the crawler system in water especially when starting running. Also it is necessary to investigate the stability in wheelie run to prevent the vehicle from falling down.

The experiments using the model were also conducted. And as the results, it is said that further experiment to evaluate the stable running can be conducted to use the model. It will enable changing the center of gravity and the center of buoyancy easily.

It is scheduled to conduct further experiments using the model and another scale model to evaluate the movability characteristics. Also it is necessary to establish the fundamental theory to express the movability characteristics of crawler system in water from starting running and to stopping running.

ACKNOWLEDGMENT

Authors would like to express our appreciation to Marine System Division of Kowa Corporation and Prof. Suzuki of Osaka University for their assistance and advice on conducting the experiment. Authors would like to also express our appreciation to Mr. Murakami of Osaka Prefecture University for his assistance on the research.

REFERENCES

[1] H. Yoshida, T. Aoki, et al, “A Deepest Depth ROV for Sediment Sampling and Its Sea Trial Result,” *Underwater Technology Conference*, 2007

[2] S. Ishibashi, H. Yoshida, et al, “Development of a Sediment Sampling System for the Deepest Ocean and Its Sea Trial Result,” *Proceedings of 17th International Offshore and Polar Engineering Conference (ISOPE)*, 2007

[3] T. Inoue, H. Osawa, H. Yoshida, et al, “Sea Trial Results of ROV “ABISMO” for deep sea inspection and sampling,” proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), 2008

[4] M. G. Bekker, “Theory of Land Locomotion” *The University of Michigan Press*, 1956.

[5] M. Abe, H. Ito, C. Nakagawa and K. Kobayashi, “Dynamic Interaction between Crawler Shoes and Road (1st Report, Basic Theory of Crawler Propulsion),” *Journal of the Japan Society of Mechanical Engineers,* Vol. 59, No. 560, pp. 107-111, April 1993.

[6] M. Abe, H. Ito, C. Nakagawa and K. Kobayashi, “Dynamic Interaction between Crawler Shoes and Road (2nd Report, Application of Basic Theory to Actual Machines),” *Journal of the Japan Society of Mechanical Engineers,* Vol. 59, No. 563, pp. 126-131, July 1993.

[7] C. Nakagawa, M. Abe and H. Ito, “Dynamic Interaction between Crawler Shoes and Road (3rd Report, Behavior of Shoes in Driving),” *Journal of the Japan Society of Mechanical Engineers,* Vol. 64, No. 617, pp. 307-315, January 1998.

[8] C. Nakagawa, M. Abe and H. Ito, “Dynamic Interaction between Crawler Shoes and Road (4th Report, Generation Mechanism of Tractive Force in Driving),” *Journal of the Japan Society of Mechanical Engineers,* Vol. 64, No. 617, pp. 316-323, January 1998.