Development of Underwater Inspection System for Dam Inspection

Concept and evaluation of simplified dynamics model

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***Abstract*— Deteriorations of social infrastructures have been progresses in Japan. To prevent accident due to its failing, effective inspection system is needed. We have been developing underwater inspection system for dam inspection which is called Dam Inspection System (DIS). It is composed by Unmanned Surface Vehicle (USV), and Remotely Operated Vehicle (ROV). USV is called Surface water platform (SWP) and ROV is called Under Water Platform (UWP) in DIS. The SWP and the UWP are connected by underwater cable, the UWP is hanging from the SWP due to negative weight in water itself. Because of this, the DIS has following advantage compared to current system such as ROV: the inspection position by the UWP can be estimated without external device, operation is easy, and no thrusters blow up the sediment while ascent or descent of the UWP. The accurate positon data is necessary for periodical inspection to evaluate aged deterioration. It is obtained from the SWP's positon and length of underwater cable while the DIS is stable in static water, but the DIS is moving, it is necessary to consider dynamics for precisely position estimation. The objective of this research is to reveal dynamic characteristic and to develop inspection position estimation method and position control method for the DIS. As the first step, we carried out the simulation using simplified model of the DIS and verification experiment. This paper report simplified model of the DIS and result of simulation and experiment. Both result indicate a DIS's characteristic that the longer cable and the lighter weight of the UWP in water makes slowly the response of the UWP against the motion of the SWP. On the other hands, we obtained that it is necessary to improve dynamics model of the DIS, and to measure parameter of testbed in accurate, because of the simulation is not reproduce motion of verification experiment sufficiently.**

Keywords—Underwater inspection; Dam inspection; ROV; USV; Underwater Cable

I. Introduction

In recent years, the deterioration of social infrastructure has become a problem in Japan since it was mostly constructed between the 1960s and 1970s. Therefore, it is concerned that the infrastructures over 50 years of age will increase the number rapidly in the next 20 years[1]. Such deteriorated social infrastructure includes the risk of accident due to structure collapse. For instance, recently, there have been cases of accidents where ceilings of highway tunnels have fallen due to deterioration. The problem of social infrastructure is widely known in Japan, and there is an increasing need to monitor the state of social infrastructure in large scale.

The dam is the one of the most important social infrastructures which needs to be inspected. The inspection is mainly done by professional divers. Many divers are needed for large-scale inspections; therefore, this approach is impractical. The cost for hireling divers is expensive especially with skilled divers. Furthermore, the manual inspection have the weakness that it can't record the inspection position in accurate, and the judgement of the condition of infrastructure is depend on a person who performs the inspection. The data for quantitative evaluations of deterioration are not provided from the manual inspection.

An alternative option in inspections conducted by divers is to use a remotely operated vehicle (ROV). The ROV has following advantages: there is no risk to human life, it is possible to have continuous inspection, and ROV can be deployed at great depths. On the other hand, ROV has following dis-advantages: the use of ROV requires a skilled operator, the camera view is easy to be blocked with sediment kicked up by the thrusters, and the accurate position of ROV is difficult to obtain in water. Acoustic positioning system or inertial navigation system are sometimes used in dam inspections [2], [3], but they are very expensive and the inspection system will be complicated.

To eliminate such problems, a new inspection system that replaces the conventional inspection is required. Therefore, we have started promoting the development of an underwater inspection system for dam inspection.

II. Proposed System and Objective of Study

On the basis of previous considerations, we propose a new underwater inspection system for dams, namely, a Dam

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Inspection System (DIS) that suspends an ROV with an underwater cable from an unmanned surface vehicle (USV), as shown in Fig. 1. For clarity, a USV of a DIS is denoted as Surface Water Platform (SWP), and an ROV of a DIS is denoted as Underwater Platform (UWP). The SWP is equipped with a cable winch, which deploys and retracts the underwater cable. The UWP is set to negative buoyant force so that it descent underwater by its own weight. Our proposed system has the following features which are useful for various problems when using an ROV:

- The inspection position by the UWP can be estimated by the position of the SWP and the run-out cable length.
- The SWP position can be obtained using general-purpose devices such as global navigation satellite system and optical positioning device.
- The vertical motion of the UWP is stable due to the balance between the UWP's weight and tensile force of the cable.
- Through the effect of above, the operation can be focused on the horizontal movement and becomes simplified.
- Since the thruster is not used for ascent or descent of UWP, less sediment is kicked up.

While the UWP position is directly beneath the SWP when the system remains in a steady state with no disturbances, the UWP's position beneath the SWP may deviate when the DIS moves or disturbance occurs owing to water flow or wind. Therefore, to know the precise position of the inspection location, it is necessary to estimate the degree of deviation.

Based on contents mentioned above, we have been motivated toward to clarify the dynamic characteristics of proposed system. Moreover, based on the characteristics, we are going to develop the inspection position estimation method and the control method for DIS. In this paper, we are going to show the simplified dynamics model, and explain the result of simulation of proposed model and verification experiment with testbed.

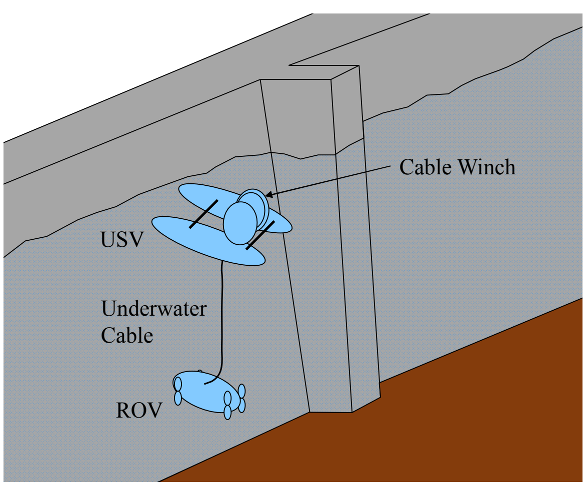

Fig. 1. Concept of Dam Inspection System

III. Simulation of Proposed System

A. Simplified model of DIS

To determine the dynamic characteristics of the DIS, a simplified model is first constructed. We assumed that the main motion pattern at the dam inspection is moved along the surface of the dike to be inspected, and designed a model on a 2D plane of the depth and horizontal movement of the DIS. In this context, we define the coordinate systems for the model as a space fixed coordinate system O_o–X_oY_o with the water surface as the zero point on the Y_o-axis, the SWP fixed coordinate system O_b–X_bY_b, a cable element fixed coordinate system O_{ci}–$X_{ci}Y_{ci}$ (here " i " is the number of the cable element), and the UWP fixed coordinate system O_s–X_sY_s (Fig. 2).

In a study on towing system, ROV, mooring float, the model of underwater cable are reported [4], [5], [6], [7]. In these models, the cable is expressed as series of cable element which has a certain length. In this study, we also used this approach and considered that the cable element is a weightless rods, and there are a point mass on each joint. Another assumption is that the connecting point transmits only force not moment. The SWP is modeled as a rigid body for which all external forces act at its center of gravity, where its center of gravity is considered to be at the zero point of the coordinate system. We also assumed that the connecting point of the cable is the center of gravity. The UWP is modeled as a rigid body such that the zero point of the coordinate system is the center of the buoyant force. Other assumptions are that the external force caused by fluid acts on the center of buoyant force, the center of gravity is positioned at l_G units lower than the center of buoyant force, and the connecting points of the cable are positioned at l_C units higher than the center of buoyant force. In addition, the SWP, cable, and UWP receive fluid drag F_V, buoyant force F_B, and gravity F_G as external forces, respectively. The fluid drag is given as (1) and (2) represented in each local coordinate system.

$$F_{Vx} = -1/2\,\rho\, S_x\, Cd_x\, \dot{x}\,|\,\dot{x}\,| \tag{1}$$

$$F_{Vy} = -1/2\rho\, S_y\, Cd_y\, \dot{y}\,|\,\dot{y}\,| \tag{2}$$

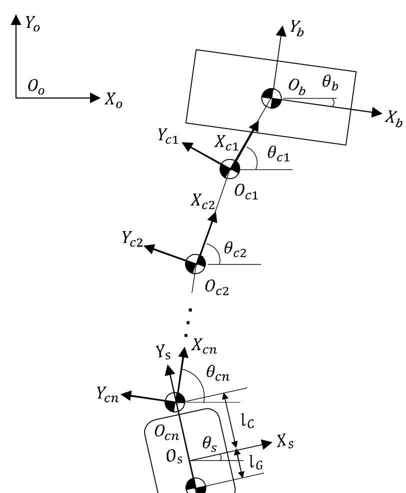

Fig. 2. Coordinate system of proposed model

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The buoyant force and gravity force are expressed in space fixed coordinate system. Buoyant force of the SWP is given as (3) and the UWP is given (4). Here, we ignore the buoyant force acting to cable. The gravity force is given as (5).

$$F_B = \rho\, S_y\, y_b\, g \tag{3}$$

$$F_B = \rho\, V_s\, g \tag{4}$$

$$F_G = -m\, g \tag{5}$$

The meaning of symbols are shown below.

- S_x, S_y : The area of respective axis
- Cd_x, Cd_y : Coefficient of fluid drag of respective axis
- V_s : Volume of the UWP

B. Result of simulation

The proposed model is simulated with the software SystemModeler. Table I shows the parameters of the model using the assumptions of testbed described below. The drag coefficients in the X_s and Y_s directions of the UWP and in the X_b direction of the SWP have been obtained from towing tests using the testbed. The number of cable element (= n) is set 3.

As an example of motion, we simulated a state in which the UWP rests just under the SWP was defined as the initial state, and a force of 19.6 (N) was applied to the SWP in the direction of X_o until the change of X_o position of the SWP reached 1.9 (m). The parameters used for this simulation are set as follows: the weight in water of the UWP (= W_{aq}) were 1.7 (kg) (m: 22.5 (kg)) and 3.5 (kg) (m: 24.5 (kg)), and the cable lengths (= L_c) were 1.3 (m), 2.8 (m), and 7.3 (m).

Fig. 3–8 shows the changes of position of the SWP and UWP in X_o axis under each condition. Regarding the trends of change in the experimental conditions, the longer the cable, the lighter the weight in water of the UWP, the response of the UWP is slower against the motion of the SWP. It will take longer for the UWP to come right under the SWP. The results showed that when the position of the SWP in X_o axis exceeded 1.9 (m) and external force had no effect, the motion with which the SWP is pulled back by the UWP generated a delayed response.

TABLE I. SIMULATION PARAMETER

	SWP	UWP	Cable element
m (kg)	82	22.5 or 24.5	$0.048 \times Lc / n$
Inertia (kg m^2)	6.2	0.6	—
Length (m)	—	—	Lc / n
S_x (m^2)	0.168	0.19	50.26×10^{-3}
S_y (m^2)	0.54	0.24	$7.7 \times 10^{-3} \times Lc / n$
V (m^3)	—	0.0208	—
Cd_x	1.7	1.73	0.9
Cd_y	0.5	1.45	1
l_C (m)	—	0.275	—
l_G (m)	—	0.2	—

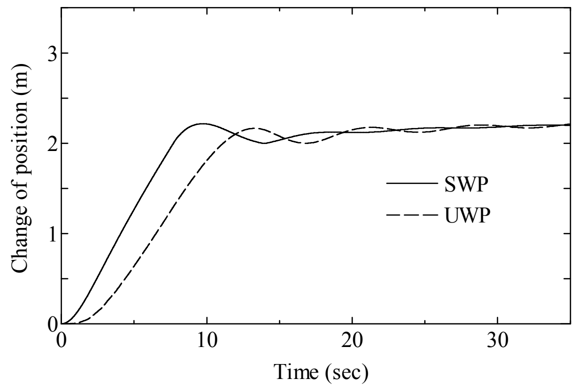

Fig. 3. Results of simulation (L_c = 1.3, W_{aq} = 1.7)

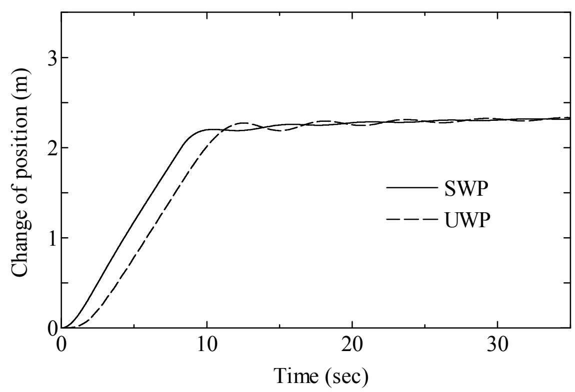

Fig. 4. Results of simulation (L_c = 1.3, W_{aq} = 3.5)

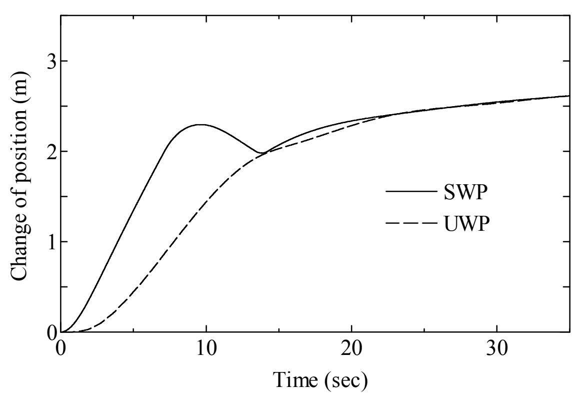

Fig. 5. Results of simulation (L_c = 2.8, W_{aq} = 1.7)

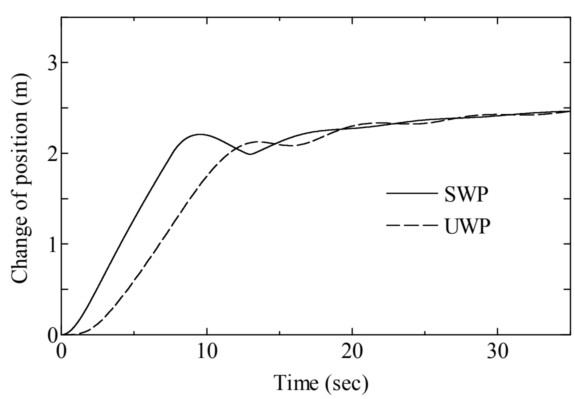

Fig. 6. Results of simulation (L_c = 2.8, W_{aq} = 3.5)

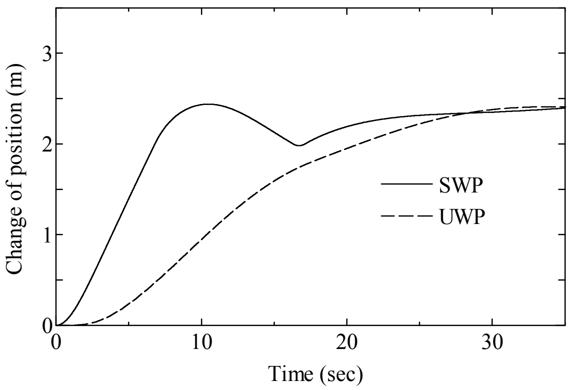

Fig. 7. Results of simulation ($L_c = 7.3$, $W_{aq} = 1.7$)

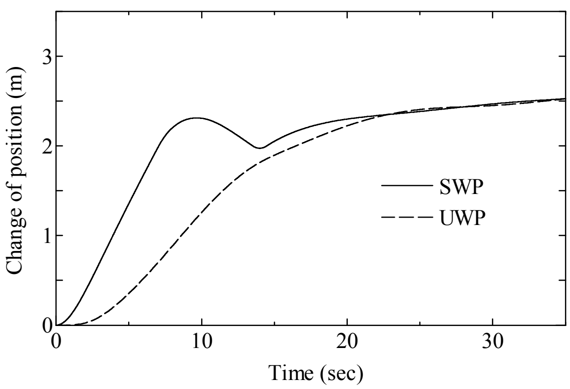

Fig. 8. Results of simulation ($L_c = 7.3$, $W_{aq} = 3.5$)

IV. Verification Experiment

To verify the validity of the simulation, we experimented with testbed and the results are given below.

A. Spesification of testbed

Fig. 9 and Table II present respectively the overview and dimensional specifications of the testbed. The power is supplied from the battery on the SWP, and the system is controlled by a wireless LAN communication through an operation interface. Hence, the system has no constraint from land. Fig. 10 shows a block diagram of the system. To operate the DIS, the first operation command to the operation interface is sent to the CPU unit on the SWP through the wireless LAN. Then, the CPU unit sends a control message to the main control board, and the sensor I/O board (according to the operation command) controls the thruster, cable winch, and sensor. As information is necessary for proper operation on the operation interface monitor, images of an IP camera on the Ethernet of the DIS and sensor information obtained from the main control board and sensor I/O board are displayed. The SWP is a twin-hulled ship with two hulls mounted on a frame on which an electronic device box and a battery box are loaded. It is equipped with four thrusters and can control surge, sway, and yaw. On the ship, a cable winch that suspends the UWP is installed. The cable winch is equipped with a cable tension compensating mechanism to prevent excessive tension that might be generated in the cable by the swing of the DIS. The external sensor is equipped with a wide-angle camera and a laser range sensor that measures the distance and the relative angle to the dam body. The UWP has the structure of a pressure hull containing an electronic device enclosed with guards. Similarly to the SWP, the UWP is equipped with four thrusters. It is also equipped with a camera with a resolution of 1920 × 1080 pixels, an LED lamp for underwater inspection, an ultrasonic range sensor that measures the distance and the relative angle to the dam body, and a laser marker for dimensional estimation of cracks.

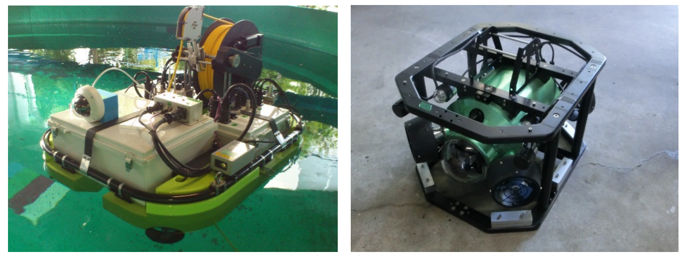
Fig. 9. Appearance of testbed; Left side is SWP, right side is UWP

TABLE II. SPECIFICATIONS OF TESTBED

	SWP	UWP
Length (m)	1.10	0.54
Width (m)	0.85	0.45
Height (m)	0.70	0.33
Weight(approx.) (kg)	82.0	22.5

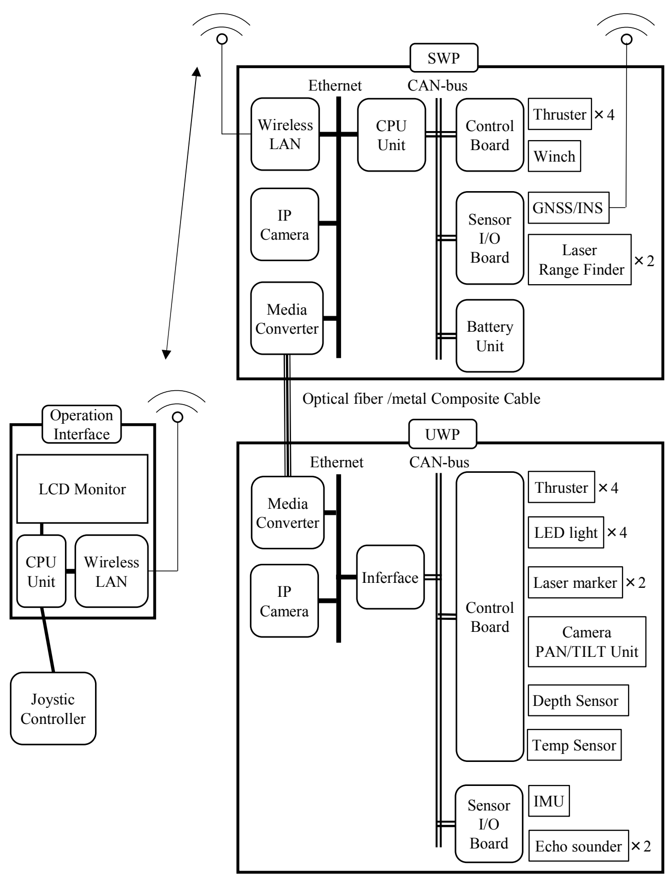

Fig. 10. System diagram of testbed

B. Experiment and result

The experiment was conducted in a pool. As in the simulation, a state in which the UWP rests just under the SWP was defined as the initial state, and the state of motion when a horizontal external force was applied to the SWP was recorded. An external force of 19.6 (N) was applied by pulling a rope wound around the SWP with a pulley and a weight until the change of position of X_o exceeded 1.9 (m). Here, the change of position was obtained from landmarks on the wall of the pool captured with the testbeds camera. To perform this measurement, the testbed was moved along the wall of the pool. The experiment was conducted under different conditions: the cable lengths (= L_c) were 1.3 (m), 2.8 (m), and 7.3 (m), and the weight in water of the ROV (= W_{aq}) was 1.7 (kg) (*m*: 22.5 (kg)) and 3.5 (kg) (*m*: 24.5 (kg)). These conditions are the same as those of the simulation. Fig. 11–15 shows the changes of position of the SWP and UWP in X_o axis under each experimental condition. With respect to the motion trends with the varying conditions, it is shown that the longer the cable and smaller the weight in water of the UWP, the response of the UWP is slower against the motion of the SWP. A similar trend is observed in the simulation. However, the motion with which the SWP is pulled back by the UWP, which was observed in the simulation, was not observed in the experiment; the state of motion does not agree completely. Apparently, the precision of the proposed model and parameters is still lacking.

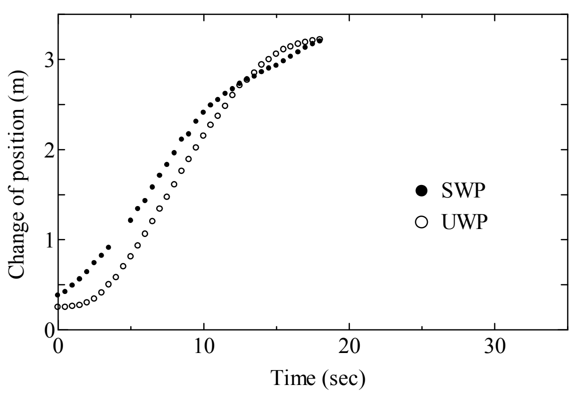

Fig. 11. Results of experiment (L_c = 1.3, W_{aq} = 1.7)

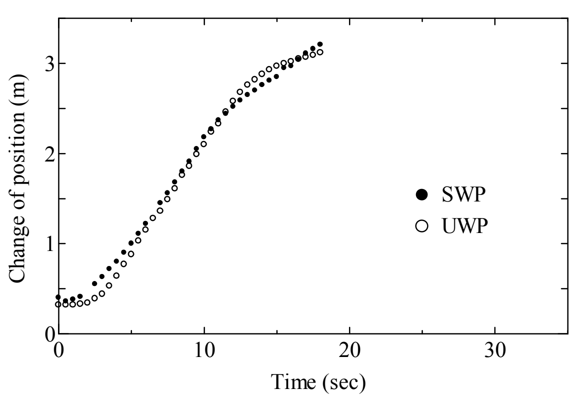

Fig. 12. Results of experiment (L_c = 1.3, W_{aq} = 3.5)

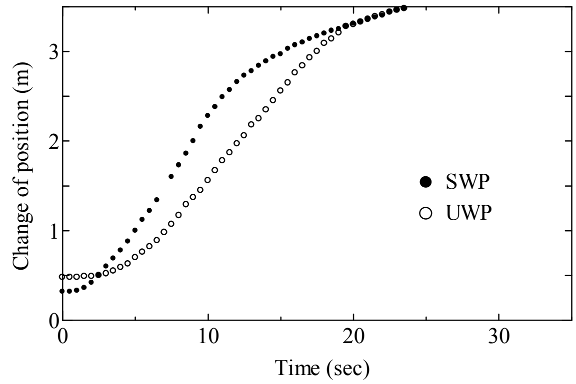

Fig. 13. Results of experiment (L_c = 2.8, W_{aq} = 1.7)

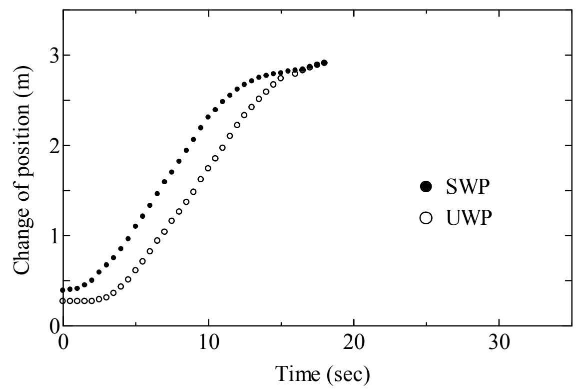

Fig. 14. Results of experiment (L_c = 2.8, W_{aq} = 3.5)

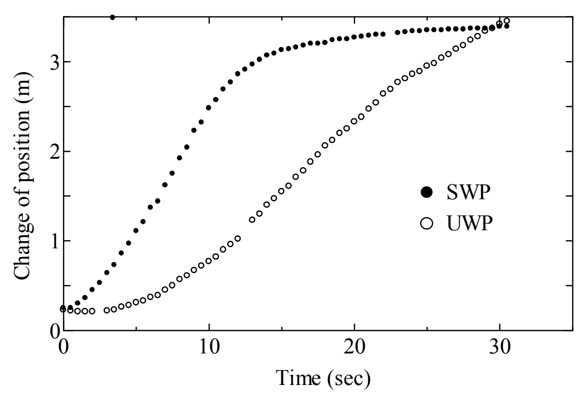

Fig. 15. Results of experiment (L_c = 7.3, W_{aq} = 1.7)

V. SUMMARY

In this study, we discussed the deterioration problem affecting social infrastructure in Japan. We proposed a new DIS consisting of an SWP and a UWP as an underwater inspection system for dams. This device is intended to address some of the problems encountered with the conventional dam inspection method. We explained a simplified model of the proposed system and showed the results of motion simulation and verification experiment using the testbed. According to our results, we observed that the longer the cable and smaller the weight in water of the UWP, the response of the UWP is slower against the motion of the SWP. However, the results of the simulation and experiments with the testbed do not completely agree; therefore, it is necessary to improve the dynamics model and obtain exact parameters of the testbed, including fluid coefficients.

VI. FUTURE WORKS

In future work, we would like to improve the accuracy of the simplified model proposed here and obtain detailed parameters of the testbed. According to the constructed model, we are also planning to develop a position estimation method and a control method for the DIS. Regarding the development of the testbed, a demonstration experiment at a real dam has been scheduled in the fall of this year.

ACKNOWLEDGMENT

This research is supported by a fund from the New Energy and Industrial Technology Development Organization.

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