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Basic Research on Underwater Docking of Flexible Structures

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Abstract - This paper deals with basic research on underwater docking of flexible underwater structures using active control system. The actively controlled underwater docking has such potentials on the installation or construction of underwater structures at deep water depth that the structures can be installed precisely on the desired point of seabed. And for the very large structure, automated construction can be possible to assemble the onshore fabricated partitioned structures on site. In this paper, the H_∞ controller is used for the flexible structural control to avoid spillovers. Basin tests were executed using two types of neutrally buoyant flexible models with ultrasound ranging system and thrusters.

1. INTRODUCTION

The actively controlled underwater docking technology will become increasingly important in the near future not only for the AUVs but also for the offshore structures especially when they must be settled or constructed at deep water depth. It allows the underwater structure to be installed precisely on the desired point of the sea bed. It also allows the very large structure to be constructed automatically on site to assemble the onshore fabricated partitioned structures.

There are some drawbacks to the conventional method using crane vessels[1,2] on the deep water installation or construction. As the water depth increases the station keeping of the vessels and their operations become more sensitive to the sea conditions. The natural period of the coupled rigged structure and the crane vessel becomes longer so that the crane manipulation to achieve the desired positioning accuracy becomes more difficult. On the other hand, the underwater docking using active control technique has the possibility that it can overcome the drawbacks mentioned above.

The actively controlled docking has another advantage that the structural flexibility is allowed during the docking operation if that flexibility is taken into account on the control strategy[3]. It means that this method can reduce surplus strengthen members needed only for the installation or assembling operation. So it will become a rational technique consistent with the recent circumstances that the offshore structures which is used at deep water depth tend to be compliant because of their large dimensions and strong requirement for light weight which leads to cost reduction.

The purpose of this paper is to examine basically the possibility of the underwater docking of the flexible structures using active control system with thrusters and ultrasound ranging system. Though there are many subjects to be examined to verify the possibility of this method, we choose the docking accuracy as the verification criterion for the first step of this research. To achieve the good docking accuracy, the H_∞ controller is used for the flexible structural control.

In order to verify the underwater docking and confirm the control algorithm, two types of basin experiments are executed. Corresponding to each experiment, two types of neutrally buoyant flexible models whose typical size is 1 m with ultrasound sensors and thrusters are used as shown in Fig.1, Fig.2. The models are consisted of some cubic rigid bodies which are connected by slender and flat beams. In the case of Fig. 1, the model is lifted from the bottom of the basin to the given altitude not stimulating the elastic responses, then made to track the given trajectory toward the targets keeping its altitude and turning its heading 90 degrees, finally to dock with fixed docking parts on the basin wall within the accuracy of ± 3mm. In Fig.2, two models are lifted from the basin bottom to the given altitude keeping each planar position not stimulating the elastic responses, then made to track each given trajectory to dock each other in floating condition, furthermore the united model is made to track the trajectory and finally dock the fixed targets on the basin wall within the accuracy of ± 5mm.

2. DYNAMICS MODELING

2.1 Coordinate System

In the formulation of the equations of motion, two coordinate systems are used as shown in Fig. 1. One is a space fixed E coordinate system O-XYZ, and another is E' coordinate system o-xyz, which is fixed at the gravity center of the structure at undeformed state. The rigid body motion is described by the motion of the origin of E' in E and elastic responses are described in terms of E'.

2.2 Equations of Motion

The strict dynamics of the structure is nonlinear because

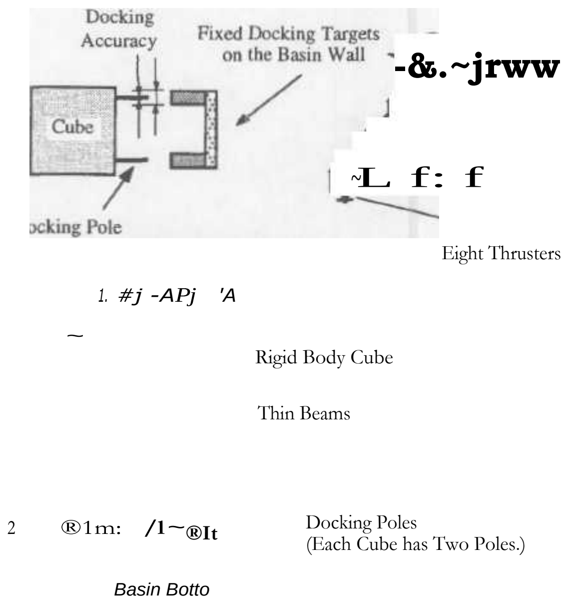

Fig. 1 Schematic View of Docking of One Structure.

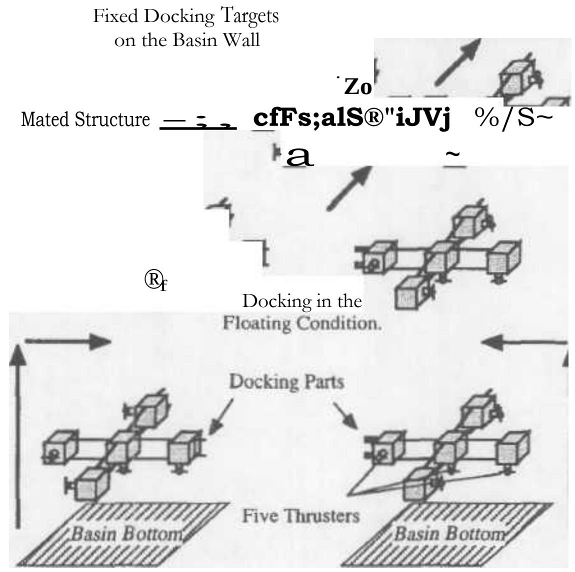

Fig. 2 Shematic View of Docking of Two Structures.

of coupling of rigid body motions and elastic responses, inertia force caused by the motion of the body axes like centrifugal force, Coriolis force etc. In the control implementation, it is not rational to consider all these effects. If the motion is able to assume that the translational velocity, rotational angles and angular velocities, elastic deformations are small enough to neglect these products, the equation of motion can linearize to rationalize the control implementation.

The derived equations of motion is generally given by partial differential equations. But partial differential equation itself is not a suitable form to be incorporated into a control algorithm. Using modal expansion of elastic displacement, the equation is replaced by an infinite set of ordinary differential equations[4].

External forces are control force, gravity force, buoyancy force, and hydrodynamic force. The strict estimation of hydrodynamic force is difficult in general so the modeling error always exists between mathematical model and real system. In this research, Morrison's equation is used to evaluate the hydrodynamic force. And the drag terms are linearized under the assumption that the structural motion is slow.

Truncating higher order modes further a finite set of ordinary differential equation is formulated to model the dynamics of the structure for controller design.

~. RJ+C OC r RJC RJ RJ=[ ] F (u
+[O^C ORJC S B R

where the subscript C, R represent control mode, residual mode respectively.

The number of control modes is N_c, residual modes is N_R, then the number of modeled modes is $N = N_c + N_R$. And B_C (N_C X M), B_R (N_R X M) represent the location of M actuators. F (M X 1) is the output of actuators.

This numerical model should be made as accurate as possible but it is important to realize that it always has the modeling errors.

3 CONTROLLER DESIGN

The characteristic of the underwater flexible structural control on the docking operation is that robustness specifications and position keeping specifications should be implemented simultaneously. The dynamics of the flexible structure shows the coupled response of translational, rotational rigid-body motion and elastic responses. The controller must be designed to have the robustness for the control and observation spillovers which are the phenomena that the truncated modes arc affected or excited by the effect of actuations or observationsts[1]. The controller must also have the robustness for the uncertainties of the formulated dynamics of the structure caused by the approximation in the formulation such as the estimation of hydrodynamic force or neglected higher order terms. In this research, hierarchical LAC/HAC(Low Authority Control/High Authority Control) and H 00 control are combined to solve above problems.

3.1 LAC/HAC

The spillover -,an be alleviated using the Direct Velocity Feedback(DVFH)161, whereby the sensors are collocated with the actuators and a given actuator force is a function of the velocity at the same point. This method can augment damping of all modes because the direct velocity includes all the modal components. Then the system becomes energy dissipative and sta le.

The DVFB is stable but it can not improve individually the performance of the specific mode as it desired. So modal control is used t achieve the desirable performance of the control modes t gether with the DVFB. This hierarchical approach is call d LAC/HAC[11]. The LQ optimal control was formulated as HAC for rigid body modes and significant lower order modes of elastic responses in this research. Modal filter w used to extract modal components of the structure becau he filter is effective even when the natural frequencies are densely spaced. Modal filter utilizes orthogonality o natural modes and it is theoretically free from observati spillover when sufficient number of sensors are used.

3.2 H oo Cont

The H 00 o timal control methodt[8, 91] can treat the robustness specifications explicitly in the controller design. It can also treat he design criteria in the frequency domain allowing the de igner to precisely shape the frequency response charact ristics according to the desired robustness and performan e specifications. Hence it is advantageous to alleviate the ontroller influences for the residual modes even when the natural frequencies of control modes and residual modes are closely spaced.

In this rese ch, H 00 controller is designed as follows. First, feedfow d and LAC/HAC feedback control force are formulated for ontrol modes by the acquired modal equations presumi g no modeling error exists. The control modes are

$$(C + {}^{I'C}\ CC \quad A_C\ C_c = B_C\ F \tag{2}$$

The control orces are constituted as follows.

$$F = F_{ff} + F_{fb} \quad {}_{hinf} \tag{3}$$

where F is -edforward control force, F_{fb} *is* LQ feedback control f. ce, F_{inf} *is* H^{oo} control force.

The feedforward force is formulated as follows to improve the traj tory tracking performance of the control modes.

$$F = {}^{BC`}(\ cr + rc \quad cr + {}^{Ac} \sim cr) \tag{4}$$

where $C_{C,}$ is derived from the given trajectory. Substituting F_{ff} into equation (2) and usingec $= Cc - Cc:$, we obtain

$$i_c + F\,c\,i_c + A_C\ e_c = B_C\,(\ {}_{Ffb} + Fhinf) \tag{5}$$

Transforming this to the state equation, the LQ feedback control force of the control modes are obtained as HAC force.

$$Ffb = -G, e_C - G_z\ i_C \tag{6}$$

Making the reference input for residual modes zero we obtain,

$$e_R = \sim_R,\ eR - {}_R,\ {}^eR = SR \tag{7}$$

then, substituting F_{fb} into equation (5), the error equations are as follows.

$$re_c 1 \quad ar_c + B_C G_2$$
$$LeRJ+L \quad {}^{BcG2} \qquad FRJLeRJ$$
$$FA_C + B_C\ G_I \quad o\ 1[\ e_c 1 \quad F^{BC} 1_{Finf} \quad [\ o\ 1 \tag{8}$$
$$L \quad B_R\ G_I \qquad ARJLeRI = LBRJ \qquad +LBRJFff$$

The second term of the right side of the equation means the effects of the feedfoward force on the residual modes. Here, we neglect this term to include in the evaluation of the modeling uncertainties.

The full order model which assumed to represent the real system is made as follows to transform the equation (8) into the state equation using $x = [e_c \quad e_R \quad i_c \quad e_R]^T$ as state vector.

$$x = Ax + BF_{inf}$$
$$y = Cx \tag{9}$$

where y is output vector. The transfer function of the full order model is

$$PFOM = C(sI-A)'B$$

The reduced order model as the nominal plant is made to transform the next equation of control modes into the state space equation with state vector $x = [e_c \quad ic]^{,r}$

$$e_c + (T'_c + B_c\ G_2)e_c$$
$$+(Ac + BcG1)ec = BCFhinf$$

The nominal plant is

$$xc = AcXC + BCFhinf$$
$$Y_c = C_c\ x_c$$

The transfer function is

$$_{PROM} = Cc\ (s\ I - A_C)\ ^{1}\ B_C \qquad (13)$$

Then the additi e modeling error is as follows.

$$dadd = FOM - {}_{PA\ OM} \qquad (14)$$

The H00 output feedback controller is made to solve the mixed sensitivity roblem by using two weighting functions because ther is a trade off relationship between the performance and robustness specifications. The one function is for robustne, s specifications which is decided to cover the additive modeli g error $_{Aadd}$ on the singular value Bode plots. The other is the sensitivity function to determine the performance speci ications.

The characterist'cs of above method is that the H ^{oo} approach and the LA C/HAC approach, can complement each other's drawbacks on the control synthesis. The transient response is comper sated by LAC/HAC approach in the time domain, while ste ' dy state response and robustness specifications are com ensated by H ^{iO} approach in the frequency domain. T erefore, it becomes easier to implement the desired and be er control specifications compared with the case that they ~ e adopted individually.

4 EXPERIME T

4.1 Experimental Setup

The purpose of e basin experiment is to examine how accurate the docki g of the flexible structure can be possible using the acti e control system with thrusters and ultrasound ranging s stem and to confirm the validity of the control algorithm hich is designed with several assumptions related earli(r. The docking accuracy is inspected whether the model can dock the docking parts within the desired range of 3 mm or ± 5 mm. The experimental set up is shown in ig. 3.

Structural Model The model is consisted of cubic rigid bodies, where eacl cube is connected to adjacent cube by slender and flat be, ms. The length between each center of two cubes is about Sm, so the whole model is about 1.Om around. A beam's N idth is 10.0 mm and the thickness is 2.0 mm or 1.0 mm to z lter the compliance of the model.

Docking Parts A docking part is consisted of two poles and their catchers s own as Fig. 1. The catcher is a circular cylinder whose ins'de diameter is variable to examine the docking accuracy. Two docking parts are arranged on the basin wall as fixer target. The pole's diameter is 10mm and the catcher's d ameter is 16mm or 20mm.

Ultrasound Ranging System The sensing accuracy is important to achieve the desired docking accuracy. The LBL(Long Base Line) system was used to measure position and deformati on of the model. This system is con-

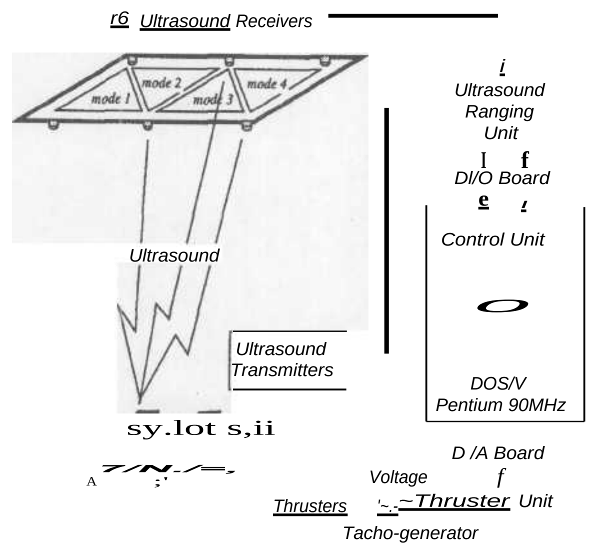

Fig. 3 Experimental Set Up.

sisted of piezoelectrical ceramic transmitters and receivers, high voltage pulse generation unit for transmitters, receiver signal processing unit, and controller unit to integrate the system. A cube has a transmitter which dispatches sharp ultrasound pulses. As shown in Fig.3 its position is detected by a set of 3 receivers selected from 6 receivers arranged in the basin, which are used to make directivity of a transmitter keep up with any cube motion along the trajectory so that the sensing accuracy becomes more precise.

Thrusters The output range of a thruster is from -0.2 N to 0.4 N. In mission 1 the model has 8 thrusters consisting of 6 for rigid body motion and 2 for first and second mode elastic responses. In mission 2 there is some restriction on the implementation of the experiment so that each model has 5 thrusters corresponding to rigid body motion except roll motion which is entrusted with its own stability.

4.2 Missions

Mission 1 The model is made to track the trajectory and finally docked the targets fixed on the basin wall shown as Fig. 1. It is lifted vertically from initial position on the tank bottom to the target's altitude keeping its XY- position, where it must be controlled to keep the attitude with a level surface and at the same time not to stimulate the elastic responses. Keeping its altitude, it is moved along X-direction, then along a quarter arc changing its heading to Y-direction, after that along Y -direction to docking targets. The trial accuracy is t 3.0 mm. The thickness of the beam is 1.0 nun. The model's total weight in air is about 13.5 kgf and its calculated natural period of the first mode is 11.8 sec.

Mission 2 As shown in Fig.2 two models are lifted vertically from each position in the same way as the case of mission 1. Then they are moved toward the predetermined position, where they are docked each other in floating condition. After that the united model is moved to dock the fixed targets on the basin wall. The trial accuracy is ± 5.0mm. The thickness of the beam is 2.0 mm. Each model's total weight in air is about 7.5 kgf and its caluculated natural period of the first mode is 5.9 sec.

In the case of mission 2, there are two choice of considering about the controller of the united model formed after the docking of two models. One choice is to make a new controller based on the dynamics of the united model which is replaced with controllers of each original model after the docking is completed. The other is to use each original controller as it stands after the docking, dealing with mutual dynamics interaction by the use of the robustness performance of each controller. The former has a difficulty how to transmit the disturbance information which is experienced by each controller before docking to the new controller of the united model. On the other hand the latter is able to treat the disturbance and the interaction in the same way as the uncertainties of the dynamics modeling. Therefore, if the controller is designed to satisfy the robustness specifications for such uncertainties, each controller ought to need no modification before and after the docking. In this paper, the latter case is examined.

4.3 Experimental Results

Mission 1 The results of mission 1 are shown in Fig.4 Fig. 7. The docking operation is succeeded within the accuracy of ± 3.0 mm. Fig. 4 shows the X directional trajectory of each rigid body of the model. The lines are crossed at about 230 sec because the model is changing its heading. Fig. 5 shows the Z directional trajectory of each rigid body. The model is successfully made to track the given trajectory without stimulating its elastic responses. The Y directional trajectory of the center cube is shown in Fig. 6. The given trajectory was changed at about 290 sec from 0.63 m to 0.68 m. This is because the buffer point was set up at 0.63m point to adjust the final position for docking to avoid the collision to the docking targets. The final docking operation was started after the positional difference between the model and docking targets at the buffer point had been within the permitted range. Fig. 7 shows the z directional Hco control forces. The Hoe control forces work through the whole experiment to compensate the modeling errors and disturbances. The maximum control force for z direction is about 0.2 N a thruster and totally 0.5 N, and in xy plane motion about 0.15 N a thruster, totally 0.35 N. The control force is very small relative to the model weight in air because the model is neutrally buoyant and given acceleration or speed on trajectory tracking is small.

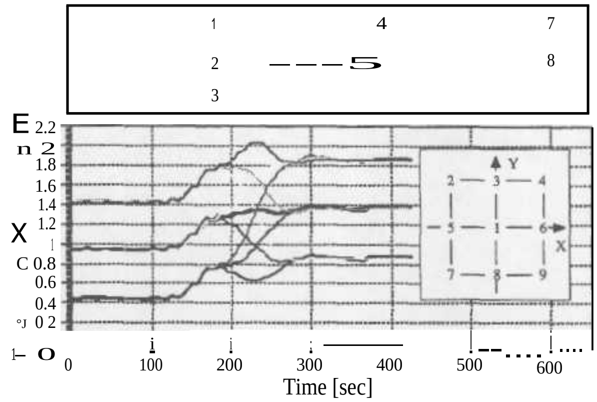

Fig. 4 Mission 1 Trajectory in X direction.

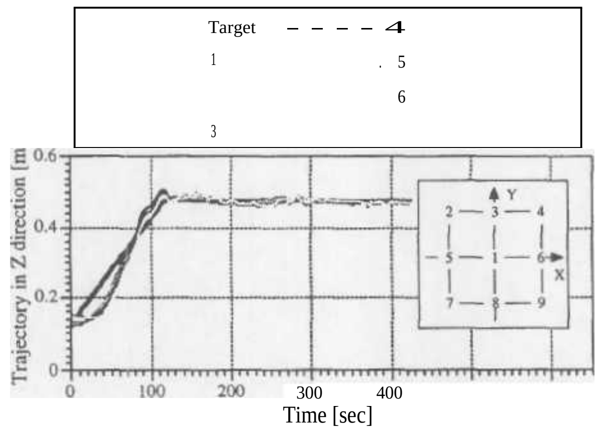

Fig. 5 Mission I Trajectory in Z direction.

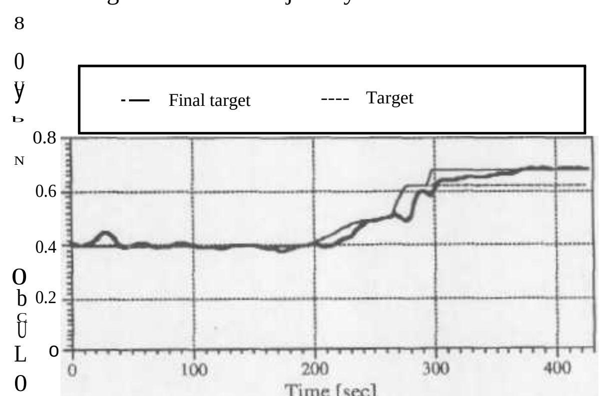

Fig. 6 Mission 1 Center Body Trajectory in Y direction.

Mission 2 Fig. 8 shows X directional trajectory in mission 2. Two models are successfully docked in floating condition within the accuracy of ± 5.0 mm and the docking operation of the united model is succeeded within the same accuracy. Structure 2-3 in the legend means the third cube illustrated in the figure of the one of two structures. The floating docking was done at about 160 sec in Fig. 8. The docking part in this case is attached at Structure 1-4 and Structure 2-3 respectively and after 160 sec the length between them becomes constant in the figure to the difference where the transmitter is attached at each cube. The docking of the united structure to the fixed targets is completed about 320 sec. In mission 2 the controllers were not changed before and after the floating docking and structural interaction of each model was successfully compensated by the robustness specifications of each controllers.

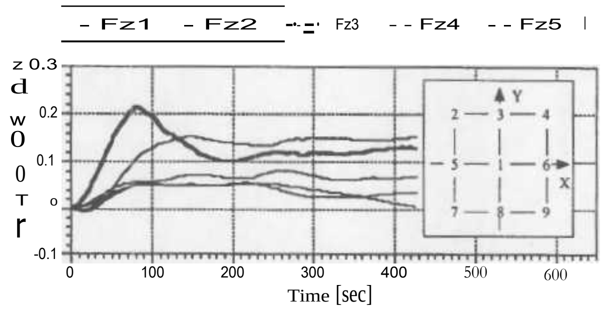

Fig. 7 Mission I H ^{oo} Control Forces in Z direction.

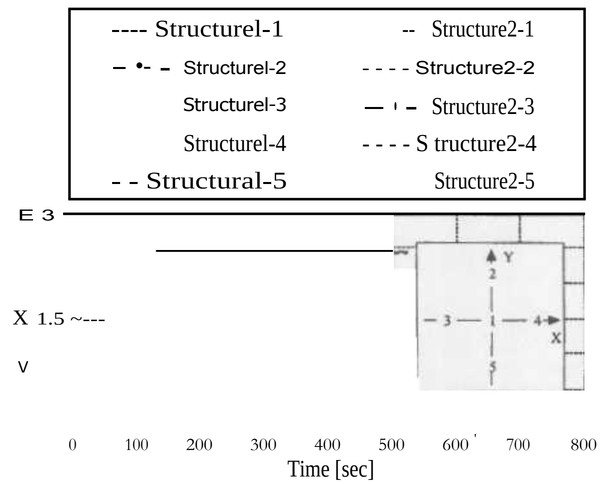

Fig. 8 Mission 2 Trajectory in X direction.

5 CONCLUSIONS

The underwater docking of flexible underwater structures using active control was discussed as one of the possible and effective solutions to the deepwater installation or construction. The H ^{oo} controller combined with hierarchical LAC/HAC feedback controller were designed. Basin experiments were executed using two types of neutrally buoyant flexible models, ultrasound ranging system and thrusters. As a result, the controller was demonstrated to be effective for the docking of flexible underwater structures satisfying the robustness specifications for spillover alleviation and performance specifications for position keeping without stimulating elastic responses.

The docking of one flexible structure whose typical size is 1 rn succeeded within the accuracy of ± 3 mm. Two structures whose typical size is 1 m were successfully docked in floating condition within the range of ±5 mm and the docking of the united model succeeded within the same accuracy.

Though there are many problems to be solved before the realization of this method, the actively controlled underwater docking has great possibility for the development of automated construction technology of large offshore structures.

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