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◉ 論　文

Active Control of Very Long and Flexible Offshore Structural Systems

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장대 유연한 해양구조계의 능동제어

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Key Words : Active Control(능동제어), Optimal Control(최적제어), Adaptive Control(적응제어), Riser(라이저), Reentry(리엔트리), LAC/HAC(계층적 제어)

초 록

본 논문에서는 금후 널리 사용되리라고 예상되는 장대 유연한 해양구조계의 동적 응답에 대한 능동제어를 다루었다. 제어기법으로는 optimal, adaptive 제어와 우주구조물의 진동제어에 사용되는 LAC/HAC 제어를 도입하여 simulation 과 모형실험을 수행하였다. 기존의 발표된 최적제어 실험결과는 만족스럽지 못하여 다시 수행할 필요성이 있었다. 그 결과, 해양구조계의 위치 및 탄성변형이 타당한 제어력 범위내에서 제어가 되어 본 연구에서 제안한 제어시스템의 유효성이 입증되었다. 또한 제어기법간의 비교를 통하여 장대 유연한 해양구조계에 대한 최적의 제어기법에 대하여 조사를 하였는데, 초기 시스템 파라미터의 추정에 오차가 있는 경우 적응제어 알고리즘의 장점을 확인할 수가 있었다.

1. Introduction

Very long and flexible offshore structural systems have been focused such as deepsea manganese nodules mining system and drilling system. Slender structures are used for deep ocean drilling, offshore oil development, ocean mining and other offshore applications. These structures which link the sea bottom and water surface become very long and inevitably flexible. Installation operations become increasingly difficult and new technology which can handle the dynamic response of flexible structures must be devised. Remotely operated installation of flexible slender structure is one of targets of technological innovation.

The riser is a very long pipe hanged from the floating body and reaching down the sea bottom in order to raise the desired underwater material.

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One of the major problems regarding the deepsea riser is reentry. In the reentry operation, the lower end of riser must be accurately positioned on the target point of the seabed and keep the position. Required positioning accuracy is high[1] and elastic deformation must be controlled for securing structural integrity.

But the very long riser shows complex 3-dimensional coupled nonlinear response due to flexibility and nonlinearity of the riser dynamics. Fig. 1 shows an example of the response of a real riser calculated by the nonlinear FEM[2] for period of 300sec and amplitude of 10m. Phase delay of 320 degree between top and bottom end of the riser is observed in the calculation result.

The guideline reentry usually performed in shallow water is not possible anymore and automatic reentry by active control is essential for a deepsea riser.

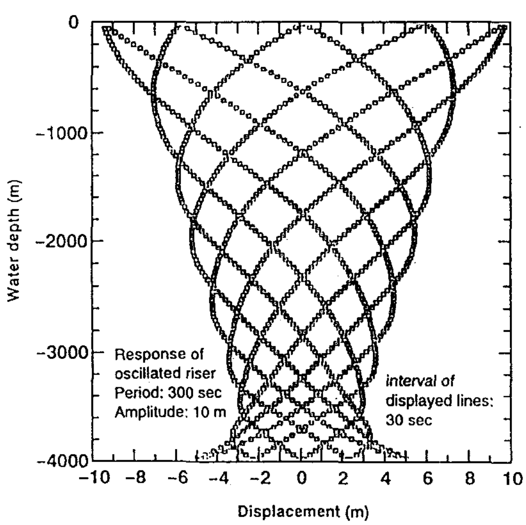

Fig. 1 Response of real riser calculated by FEM.(Oscillation amplitude is 10m and period is 300sec. Time interval of displayed lines is 30sec.)

In previous papers[3,4,5], the author presented a basic research on automatic reentry by optimal and adaptive control. An adaptive control is adopted in order to deal with hydrodynamic force terms like added mass and drag coefficient. The partial differential equations of coupled motion of floating body and riser are derived using Hamilton's principle and effectiveness of optimal and adaptive control system is demonstrated by time domain simulation and basin experiment in terms of 2-dimensional responses.

However, experimental results were not so satisfactory because of the effect of electrical noise of the thruster used in the experiment. In particular, experimental results by optimal control were so bad and it is necessary to perform the experiment over again. This paper is an updated experimental version of the previous work[3].

In the present study, the riser reentry systems formulated by optimal and adaptive control are tested by a basin experiment with 1/2000 scale model and computer simulation to obtain the more effective control strategy. The advantage of adaptive control is found through the simulation result with the wrong initial parameter value.

2. Control Method and Adaptive Controller

Optimal control is used to control the coupled dynamic responses of the floating body and the riser. The equations of coupled motion of the floating body and the riser[3] are rewritten as

$$\dot{X} = AX + BU \qquad (1)$$

where X = state vector whose elements are displacement of the floating body, deflection of the riser and their time derivatives. U = control force vector. Objective function of the control is

$$I_p = \int_0^{\infty} [\, X^T Q X + U^T R U] dt \qquad (2)$$

where Q and R = weighting matrices on X and U. Using the solution P of Riccati equation, control force U is given by

$$U = -R^{-1}B^{T}PX \tag{3}$$

where Riccati equation is

$$\dot{P} + A^{T}P + PA + Q - PBR^{-1}B^{T}P = O$$

Moreover, hierarchical control, LAC/HAC(Low Authority Control/High Authority Control)[6], which is originally developed for vibration control of LFSS(Large Flexible Space Structure)[7], is adopted to control deflection of a very long and flexible riser. The role of LAC is to augment damping of whole system. DVFB (Direct Velocity Feedback control)[7], which collocate actuators and velocity sensors, is used because the dynamic system is made energy dissipative and, consequently, robust against parameter variations[6]. After the system is made insensitive to disturbances, several significant modes are controlled by IMSC(Independent Modal Space Control)[8,9] as HAC. When selected significant modes are controlled, infinite residual modes are left uncontrolled and the system instability(spillover) may possibly be caused by the interaction between controlled modes and uncontrolled modes. Damping introduced by the LAC prevents this type of instability. Fig. 2 shows block diagram of control system by LAC/HAC.

By the way, estimation error of system parameter and nonlinear hydrodynamic force may make the result of conventional optimal control inaccurate or unstable in water. The nonlinear hydrodynamic term like drag coefficient is easily varying according to operation condition and environment. An adaptive control is adopted in order to deal with hydrodynamic force terms like added mass and drag coefficient. PE(Persistently Exciting) input[10] is an external input with many different frequencies and forces the system parameter estimates to converge to the true parameter values. In adaptive control, it is necessary for perfect identification of system parameters. But to use a PE input is not practical and it may do damage to a very flexible structure like a riser.

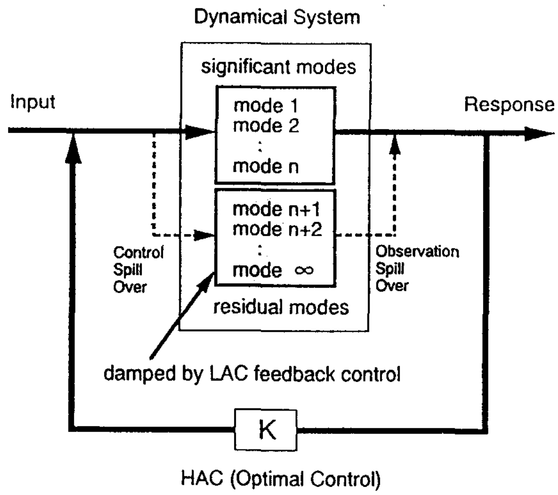

Fig. 2 Block diagram of control system by LAC/HAC

Therefore, an adaptive control algorithm, which does not require a persistently exciting input, derived for MIMO(multi-input multi- output) linear discrete-time system by Ossman and Kamen[11], is selected as an adaptive controller in the previous[4,5] and present study.

2.1 System Definitions and Assumptions

The assumptions made on the unknown plant are: 1) an upper bound on the system order is known, 2) the system parameters belong to known bounded intervals, and 3) the plant is stabilizable for all possible values of the unknown system parameters ranging over the known intervals.

The system to be regulated is the MIMO linear discrete time system described by

$$y(k) = -\sum_{j=1}^{n} A_j y(k-j) + \sum_{j=1}^{n} B_j u(k-j) \quad (5)$$

In eqn.(5), y(k) is output vector and u(k) is control input vector. The system described by eqn.(5) can rewritten in the following form convenient for parameter estimation:

$$y(k) = D^T \phi(k-1) \quad (6)$$

$$\begin{aligned} where,\ D^T &= [-A_1 \cdots -A_n\ B_1 \cdots B_n] \\ \phi^T(k-1) &= [y(k-1) \cdots y(k-n)\ u(k-1) \cdots u(k-n)] \end{aligned}$$

In certain applications, some of the entries in the system matrix D will be known a priori. Since it is not necessary to estimate known parameters, a scheme for separating the known parameters from the unknown parameters is advantageous. This is accomplished by rewriting eqn.(6) in the following form:

$$y(k) = \theta^T \phi_a(k-1) + \psi^T \phi_b(k-1) \quad (7)$$

The matrix θ contains all of the unknown entries in D while the matrix ψ contains only those entries of D which are known a priori. The vectors $\phi_a(k-1)$ and $\phi_b(k-1)$ are regression vectors whose components come from $\phi(k-1)$.

2.2 Parameter Estimation

Consider the linear discrete time system described by ARMA (Auto-Regressive Moving Average) model like eqn.(7) and the parameter estimation algorithm is given by

$$\begin{aligned} \theta(k) &= \theta(k-1) - P(k-1) f(\theta(k-1)) + \\ &\frac{P(k-1)\phi_a(k-1)}{\eta_{k-1}^2 + \phi_a^T(k-1) P(k-1) \phi_a(k-1)} \\ &\times [y^T(k) - \phi_b^T(k-1)\psi - \phi_a^T(k-1)\theta(k-1)] \end{aligned}$$

$$P(k) = P(k-1) - \frac{P(k-1)\phi_a(k-1)\phi_a^T(k-1)P(k-1)}{\eta_{k-1}^2 + \phi_a^T(k-1)P(k-1)\phi_a(k-1)}$$

$$0 < P(0) = P^T(0) < 2I$$

$$f_{ij}(k-1) = \begin{cases} \theta_{ij}(k-1) - \theta_{ij}^{\max}, & when\ \ \theta_{ij}(k-1) > \theta_{ij}^{\max} \\ \theta_{ij}(k-1) - \theta_{ij}^{\min}, & when\ \ \theta_{ij}(k-1) < \theta_{ij}^{\min} \\ 0, & when\ \ \theta_{ij}(k-1) \in [\theta_{ij}^{\min}, \theta_{ii}^{\max}] \end{cases}$$

$$\eta_{k-1} = \begin{cases} 1, & when\ the\ determinant\ of\ P(k) > \varepsilon, \\ \max(1, \| \phi_a(k-1) \|), & otherwise. \end{cases} \quad (8)$$

where ε is any small positive number.

2.3 Adaptive Regulator

The state-space observer form realization for the system described by eqn.(1) is given by

$$x(k+1) = Fx(k) + Gu(k), \quad y(k) = Hx(k) \quad (9)$$

where,

$$F = \begin{bmatrix} -A_1 & I & & \\ -A_2 & & I & \\ \vdots & & & \ddots \\ -A_{n-1} & & & I \\ -A_n & & & 0 \end{bmatrix}, G = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_{n-1} \\ B_n \end{bmatrix}, H = [I\ 0\ \dots\ 0]$$

The control force is given by

$$u(k) = -L(k)x(k) \quad (10)$$

$$L(k) = [G^T(k) R_k G(k) + I]^{-1} G^T(k) R_k F(k)$$

$$\begin{aligned} R_{k+1} &= Q + L^T(k) L(k) + \\ &(F(k) - G(k)L(k))^T R_k (F(k) - G(k)L(k)) \end{aligned}$$

where L is feedback gain, Q is weighting matrix, R is the solution to the Riccati difference equation.

The estimation algorithm has no need to calculate inverse matrix and the regulator requires the solution of only one iteration of the Riccati difference equation at each point in time. This adaptive controller has the great practical merit of computational simplicity.

3. Model Experiment

Simulation results for experimental model and real system by optimal and adaptive control are very satisfactory[3,4,5]. Table 1 shows specifications of the experimental model and real system. However, the equations of motion used in the simulation are linearized ones. Moreover, the effect of unmodeled dynamics and nonlinearity and uncertainty of hydrodynamic parameter which cannot be considered in the simulation also exist. The basin experiment is carried out to confirm the function of control system.

Experimental setup and model are not presented here, as they were demonstrated in the previous papers[3,4,5], to which details are referred. Block diagram of control system is shown in Fig. 3.

Table 1 Specifications of the experimental model and real system.

Floating body	Model	Real system
Mass(kg)	14.083	1.5×10^7
Riser	**Model**	**Real system**
Length(m)	1.777	4000
Outer diameter(m)	0.064	0.406
Young's modulus(N/m^2)	6.3×10^9	2.1×10^{11}
Moment of inertia of section(m^4)	4.667×10^{-12}	5.541×10^{-4}
Weight in air(N)	22.54	3.0×10^7
Weight in water(N)	1.13	1.5×10^6

3.1 Experimental Result by Optimal Control

In the experiment, the control starts in the current with displaced position of the floating body and initial inclination of the riser. Deformation and inclination of the riser are suppressed and the lower end of the riser is brought right over the target on the basin floor and then the position is kept by the control.

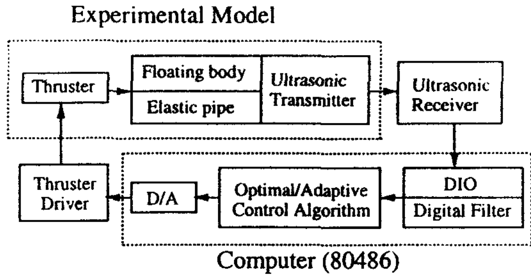

Fig. 3 Block diagram of control system(experiment)

Displacement of the floating body is shown in Fig. 4. Solid line shows the case in which both the floating body and the riser are controlled. Broken line shows the case without control of the riser. Control accuracy is 5mm which is 0.25% of the water depth 2m.

Fig. 5 shows displacement of the lower end of riser from the target. Solid line shows the case in which both the floating body and the riser are controlled and the lower end of riser is kept right under the floating body. Broken line shows the case in which only the floating body is controlled. By controlling the riser, displacement of the lower end of the riser from the target, which is induced by current, is decreased from 67mm to almost zero. Fluctuation amplitude of the lower end of the riser about mean displacement is 11mm for controlled case but 22mm for uncontrolled case.

Motion of out of plane of the floating body is independently controlled by conventional PID control and it makes the experiment purely 2-dimensional problem. The control performance shown in Fig. 6 is also satisfactory. Average control force required for the position keeping of the floating body is 15gf and the required control forces at midpoint and lower end of the riser are 1.5gf.

In the present study, moreover, the attempt is

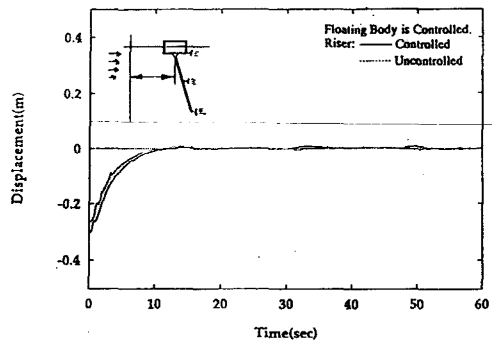

Fig. 4 Displacement of floating body by optimal control.

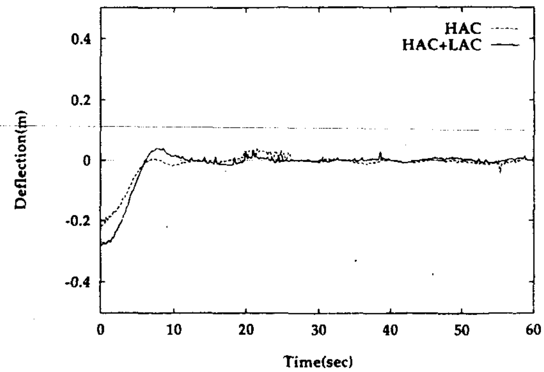

Fig. 7 Deflection of riser at midpoint by HAC and LAC/HAC.

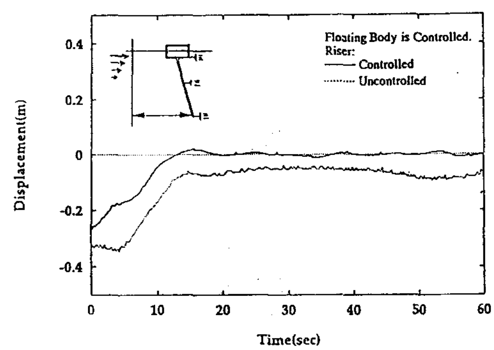

Fig. 5 Displacement of lower end of riser by optimal control.

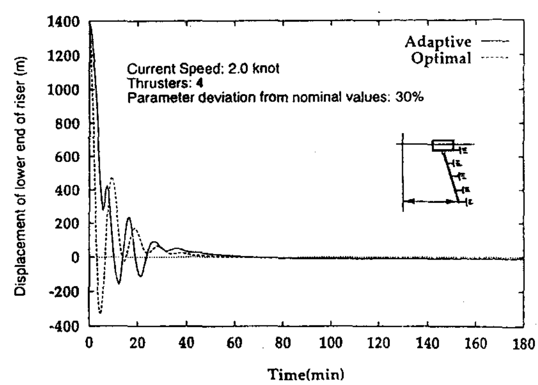

Fig. 8 Displacement of lower end of riser for real system.

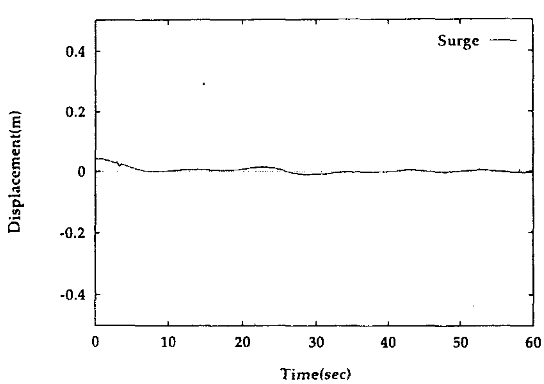

Fig. 6 Displacement of out of plane of floating body.

made to adopt LAC/HAC for control of the riser deflection in the experiment. Optimal control and DVFB are used as HAC and LAC, respectively. Fig. 7 shows deflection of the riser at midpoint when the model is controlled by only HAC and by LAC/HAC. Due to hydrodynamic damping, the riser model does not show higher mode response in the experiment, and it can be known that optimal control alone can function well. Experimental results by adaptive control were demonstrated in the previous papers[4,5], to which details are referred.

3.2 Discussion

Control accuracies for displacement of the floating body by both the optimal and adaptive control are very satisfactory. Control accuracy for position keeping of the lower end of riser by optimal control is also satisfactory. But the accuracy for position keeping of the lower end of riser by adaptive control was not satisfactory, though the displacement was reduced by 50% compared with uncontrolled case.

Nevertheless we can think that meaningful results were obtained for realization of the automatic reentry system by adaptive control. Adaptive control is well known to be very difficult to implement because unknown system parameters must be estimated on real time[10].

Simulation calculation is carried out for the comparison of performance of optimal and adaptive control. The simulation is computed for real system with the initial system parameters deviated from the true values by 30%($C_m=1.4$, $C_d=0.6$). Inertia coefficient C_m, drag coefficient C_d which are uncertain hydrodynamic parameters, depend on KC number(= UT/D, where U and T are the velocity amplitude and period of the wave, D is the diameter.) and Reynolds number[12], and it is assumed to be $C_m=2.0$, $C_d=1.0$ as the true values in this study.

Fig. 8 shows displacement of the lower end of the riser for real system shown in Table 1. Initial displacement of the floating body and inclination of the riser are 1000m and 0.1rad, respectively. Current velocity is 2.0knots (1.0m/sec) at the surface of the sea and zero at water depth 1000m. Up to 12th deflection modes of the riser are considered in the calculation. Solid line shows the result by adaptive control and broken line shows the case by optimal control. The result by adaptive control shows better transient response and smaller overshoot than that by optimal control. The stationary positioning error, which is the net effect of current, remains. This value can be canceled out by feedforward control or position shifting of the floating body.

4. Conclusion

In the present study, the optimal and adaptive control theories are applied for the riser reentry system. An adaptive control is adopted in order to deal with uncertain hydrodynamic terms like added mass and drag coefficient. And those two algorithms are compared through the model experiment and computer simulation to obtain the more effective control technique for the offshore structural system. Through the present work, the main conclusions can be drawn as follows:

1) For known system parameter case, the coupled responses of the floating body and riser are actively controlled by optimal control. Deformation of the riser is well suppressed and the position of the lower end of the riser is kept right over the target. This paper is an updated experimental version of the previous work[3].

2) Adaptive control system is formulated for uncertain system parameter case. Controlled responses of riser are compared with optimal control with gains derived for nominal values of parameters. Adaptive control shows better result when parameter deviation exceeds by 30% from nominal values.

3) Promising results are obtained for the synthesis of a 2-dimensional control system for position and elastic response of a very long and flexible offshore structural system in the previous and present study. The research result obtained from the present study can be extended

to a 3-dimensional real system through further study. If the effect of twisting response is insignificant, the same control system can be applied to another 2-D plane which is perpendicular to the present 2-D plane. Otherwise, the twisting effect must be considered for formulation of 3-D control system. The author has a plan to do research on 3-D problem continuously.

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References

1) Brink, A.W., J.S. Chung, "Automatic Position Control of a 30,000 Tons Ship during Ocean Mining Operations", OTC4091, pp.205-224, 1981
2) Suzuki, H., K. Yoshida, "Three Dimensional Nonlinear Dynamic Analysis Method of Underwater Line Structure and its Validation", Trans. ASME, J. Offshore Mechanics and Arctic Engineering, Vol.114, No.3, pp.139-145, 1992
3) Suzuki, H., K. Yoshida, D.H. Nam, et al, "Automatic Reentry of Deepwater Riser by Active Control", Journal of SNAJ, Vol.174, pp.865-874, 1993 (in Japanese)
4) Nam, D.H., "Automatic Reentry of Deep water Riser by Adaptive Control", KCORE, J. of Ocean Eng. and Tech., Vol.10, No.1, pp.108-118, 1996 (in Korean)
5) Nam, D.H., H. Suzuki, K. Yoshida, "Reentry of Deepsea Riser by Adaptive Control", Proceedings of International Offshore and Polar Engineering Conference, Vol.2, pp.107-114, 1997
6) Aubrun, J.N., "Theory of the Control of Structures by Low Authority Controllers", J. Guidance and Control, Vol.3, No.5, pp.444-451, 1980
7) Balas, M.J., "Direct Velocity Feedback Control of Large Space Structures", J. Guidance and Control, Vol.2, No.3, pp.252-253, 1979
8) Meirovitch, L., H. Oz, "Modal-Space Control of Large Flexible Spacecraft Possessing Ignorable Coordinate", J. Guidance and Control, Vol.3, No.6, pp.569-577, 1980
9) Meirovitch, L., H. Baruh, "The Implementation of Modal Filters for Control of Structures", J. Guidance and Control, Vol.8, No.6, pp.707-716, 1985
10) Astrom, K.J., B. Wittenmark, "Adaptive control", Addison Wesley, 1989
11) Ossman, K.A., E.W. Kamen, "Adaptive Regulation of MIMO Linear Discrete Time Systems Without Requiring a Persistent Excitation", IEEE Trans. AC Vol.AC-32, No.5, pp.881-889, 1987
12) Faltinsen, O.M., "Sea Loads on Ships and Offshore Structures", Cambridge University Press, 1990