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DESIGNING ADVANCED RUDDER ROLL STABILIZATION SYSTEM
- Using High Power with Small Size Hydraulic System -

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ABSTRACT

This paper will outline the various stages in the design and development of advanced rudder roll stabilization system based high slew rate steering system. The slew rate means rudder angle change rate. First, this paper introduces a high slew rate steering system with Electric hydraulic system (EHS). The basic concept of EHS system is to combine the hydraulic power source system and actuator system with controlling the speed of electric motor of hydraulic pump depending on the condition required to the actuator. Next, this paper presents the adaptive rudder roll stabilization system based on a multivariate auto-regressive model that is called Multivariate Auto-regressive Rudder roll Control System (MARCS). Finally, conclusions and discussions based on full scales experiments are summarized.

KEY WORDS

Electric hydraulic system (EHS), Multivariate Auto-regressive Rudder roll Control System (MARCS), Adaptive control

INTRODUCTION

The purpose of rudder roll stabilization system is put on roll reduction as well as course keeping by appropriate steering using only rudder. This paper will outline the various stages in the design and development of advanced rudder roll stabilization system based high slew rate steering system and adaptive control. The slew rate means rudder angle change rate.

The approach to this control system is based on a multivariate auto-regressive model that is called Multivariate Auto-regressive Rudder roll Control System (MARCS) [1][2].

First, this paper introduces a high slew rate steering system with Electric hydraulic system (EHS). The basic concept of EHS is to combine the hydraulic power source system and actuator system with controlling the speed of electric motor of hydraulic pump depending on

the condition required to the actuator [3].
The effectiveness of any roll stabilization system depends on the magnitude of the stabilization moment that can be applied to the ship. For the MARCS to be effective, it is necessary to change faster in slew rate. In case of applying EHS to steering system which is one of the most typical hydraulic systems in ship's equipment and have good results with roll reduction.
Next, this paper presents application of the batch adaptive control based on a locally stationary auto-regressive model. The control gain of conventional MARCS does not change through the navigation at sea. However wind and wave can be regarded as stationary for a short time, it is necessary from a viewpoint of long-time observation to consider that the property of the stochastic process will be changed and be non-stationary [4].
Finally, conclusions and discussions based on full scales experiments are summarized. The EHS can save power consumption on average by over 80(%) in comparison with a conventional hydraulic steering system. The advanced MARCS using EHS reduced the roll motion in average with 30(%) -- 50(%) comparison with the conventional auto-pilot.

ELECTRIC HYDRAULIC SYSTEM (EHS)

In conventional hydraulic system, power source and actuator are separated as shown in Figure 1. The power source is designed to meet maximum required flow-rate of actuator. Electric motor of hydraulic pump is operated with constant speed all the time. This system should be controlled with servo-valve and remain is returned to oil tank through relief valve. In some conditions, a variable mechanism is applied to the pump and actuator, but the controllability is not sufficient to cover all condition. Also in those systems, the power source ant actuator are generally equipped separately and connected with piping complexity on the floor. In those piping, fluid vibration is a usual problem that causes to operate noise.

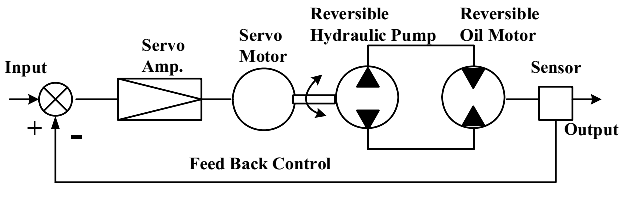


Figure 1 Servo Control of EHS

The basic concept of EHS is to combine the hydraulic power source and actuator with controlling the speed of electric motor of hydraulic pump depending on the condition required to the actuator. The EHS is developed as a new revolution control techniques for electric motor. The construction of EHS is shown in Figure 2. The concept of this system is that the speed of electric motor of hydraulic pump is controlled with inverter against the load change, so it can supply required volume of system oil to an actuator.
As the result, such components as servo-valve, relief valve would be able to be removed from hydraulic system. This system could improve the efficiency of system, because the hydraulic pump operates whenever the actuator is moving.

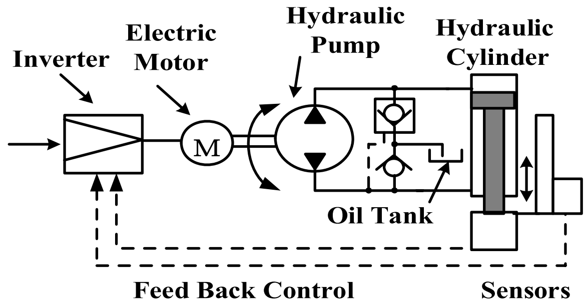


Figure 2 EHS Hydraulic System

The basic components of EHS are as follows [6],

a. Reversible Hydraulic Pump:
   Suction or discharge of hydraulic pump should be changed with the direction of revolution.
b. Servo motor or AC-motor with inverter:
   The motor for hydraulic pump should equip with speed control function.
c. Reversible motion actuator:
   The actuator should have the function of reversible motion.
d. Oil tank and piping:
   The volume of oil tank should cover total volume of components. Only supply line and return line to be equipped with.
e. Control system:
   The motion of the actuator should be controlled directly with the pump revolution.

DESIGN OF EHS STEERING SYSTEM

The conventional steering system is equipped with steering wheel, autopilot, rudder operating system, hydraulic source system and rudder. In case of applying EHS to steering system, the rudder operation system and hydraulic source system of conventional system are though to be replaced with it. Supposing that the pump characteristics using servo controlled servo-motor is proportional function, the design of EHS steering system is shown in Figure 3.
This system is composed of servo motor, servo pack, reversible hydraulic pump and can drive high slew rate not only the realization of small size reduction of weight of steering system. In case of applying EHS to steering, the rudder operation system and hydraulic power unit of conventional system are through to be replaced with it.

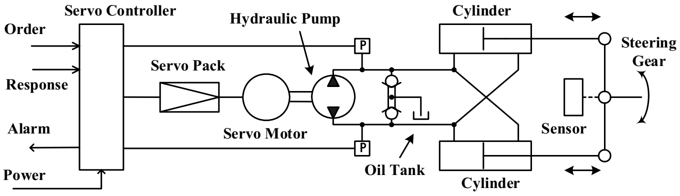


Figure 3 Design of EHS Steering System

CONVENTIONAL MARCS

As one of the authors, has demonstrated in paper [4], Multivariate Auto Regressive eXogenous (MARX) model expressed by

$$X(n) = \sum_{m=1}^{M} A(m)X(n-m) + \sum_{m=1}^{M} B(m)Y(n-m) + U(n) \quad (1)$$

is powerful stochastic model in designing a roll reducible autopilot system, where X(n) is 2 dimensional vector of controlled variable (r); yaw and roll. Y(n) is 1 dimensional vector of control variable(l): rudder angle. U(n) is Gaussian white noise. The order M of this model is obtained by AIC (Akaike's Information Criterion [5],

$$AIC(M) = N\log(\det(d_{r,M})) + 2r(r+l)M + r(r+l) \quad (2)$$

$d_{r,M}$ is the covariance matrix of the residual of the MARX model. N is number of data. The optimal order in the MARX model is determined by minimizing the value of AIC. Based on the modem control theory, this model can be transformed to state space representation.

$$Z(n) = \Phi Z(n-1) + \Gamma Y(n-1) + W(n) \quad (3)$$
$$X(n) = HZ(n)$$

where Z(n) is the state vector and Φ is the transfer matrix that controls the transition of the state Z(n). Y is the observation vector. In order to evaluate a performance of the control, quadratic criterion function optimal in the **I** suitable interval.

$$J_I = E\left\{\sum_{n=1}^{I}\left\{Z^T(n)Q(n)Z(n) + Y^T(n-1)R(n)Y(n-1)\right\}\right\} \quad (4)$$

Q and R are the weighting function for the controlled and the control variables, respectively. The optimal control law which minimizes J_I under constraint of the above state space equation is given by a feedback law with the stationary gain G. Then the optimal control law can be represented by

$$Y(n)=GZ(n) \quad (5)$$

PROTOTYPE EHS STEERING SYSTEM

To confirm the effectiveness of EHS, the prototype EHS is established to the conventional steering system. The actual ship for experiment is the training ship "SHIOJI MARU" of Tokyo University of Marine Science and Technology. The principal particulars are shown in Table 1. The basic specification of steering system is shown in Table 2.

Table 1 Principal Particulars of "SHIOJI MARU"

Hull	Length (Lpp)	46.0 (m)	Propeller	Type	Cpp
	Breadth	10.0 (m)		Aspect Ratio	1.47
	Draft	3.8 (m)		No. of Blade	4
	Gross Ton	425.0 (ton)	Engine	Type	Diesel
	GM	1.48 (m)		HP	1400 (HP)
	KB	1.56 (m)		RPM	700 (rpm)
	Roll Period	6 – 7 (sec)		No.	1
Rudder	Area	4.25 (m^2)			
	Aspect Ratio	1.47			
	Slew rate	2.3 – 4.6(deg/s)			

Table 2 Basic Specification of Steering System

Actuator Hydraulic Cylinder	Cylinder Bore	100 (ϕ)
	Rod Diameter	56 (ϕ)
	Stroke (hard to hard)	427 (mm)
Power Unit	Power (pole)	3.7 (kw) / set * 2
Electric Motor	Performance	2.3 – 4.6 (deg/s) [1 set – 2 sets]
	Revolution	1500(rpm)
Hydraulic Pump	Type	Vane Pump
	Delivery min.	23 (l/m) at 12.3(MPa)

The hydraulic steering circuit of this ship is shown in Figure 4. Applying the conventional system, the flow rate becomes constant at its upper limit when the movement of rudder angle is large. It is ordinary as operating that the slew rate is 2.3 (deg/s) with one set of power unit and also using two sets of power units, it can drive 4.6 (deg/s).

Table 3 Comparison of Conventional and EHS Steering System

Item	Conventional	DDVC
Size (H * B * D)	0.8 * 1.2 * 0.6 (m)	0.3 * 0.7 * 0.25 (m)
Weight	600 (kgf)	60 (kgf)
Electric Motor	3.7 (kW) * 2	4 (kW)
Slew Rate	max. 4.6 (deg/s)	max. 10.2 (deg/s)
Oil Volume	500 (little)	20 (little)
Flux adjustment	Servo valve	Hydraulic pump
Power Consumption	————	90 (%) reduction
Noise Level	————	10 (dB) reduction
Installation & Maintenance	Dock & Difficult	Quay & Easy

The conventional steering system is equipped two sets of AC electric motor and servo valve with large oil tank. The EHS steering system is equipped only servo motor and hydraulic pumps with very small oil tank. The comparison of typical performances of conventional and EHS steering system are shown in Table 3.

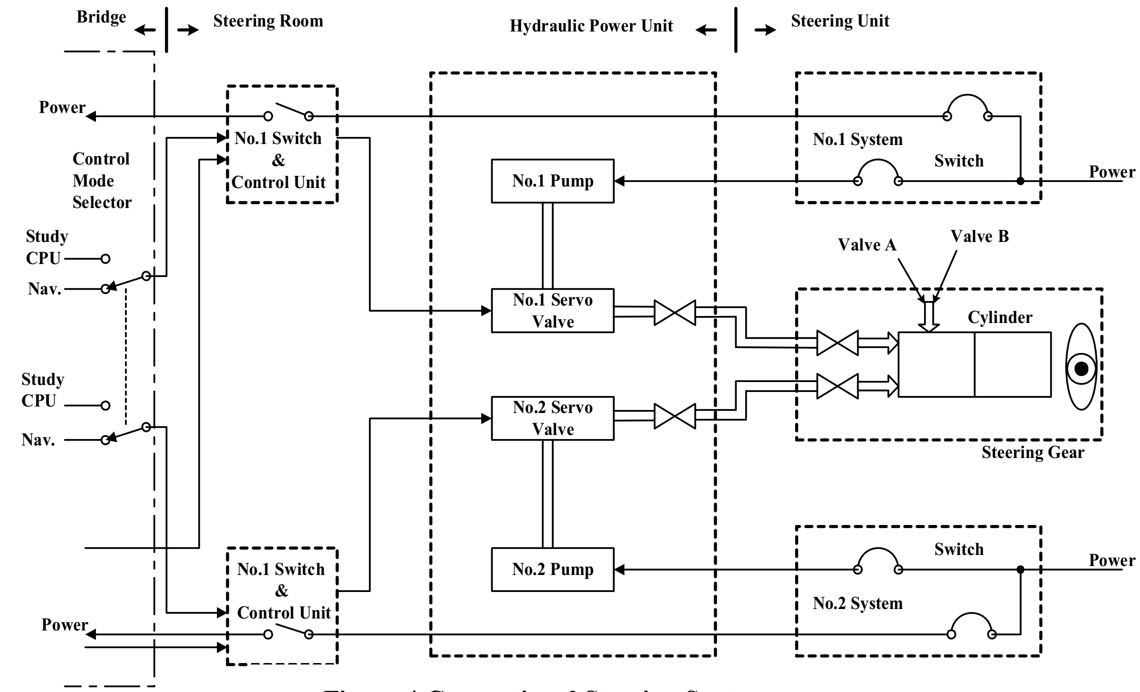


Figure 4 Conventional Steering System

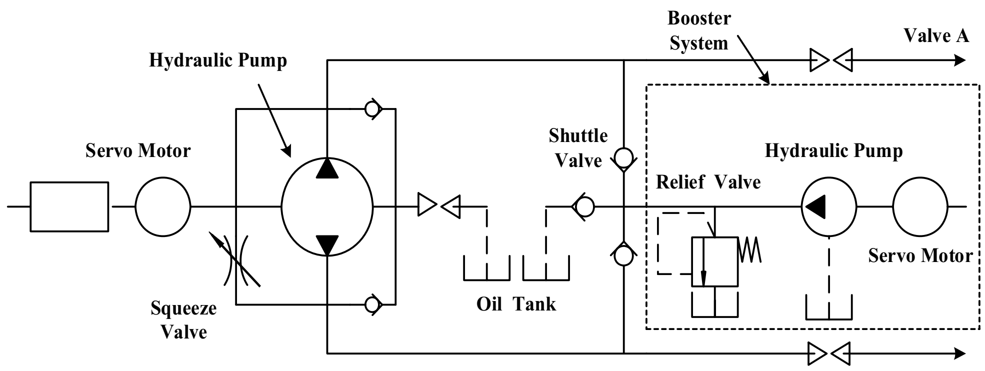


Figure 5 EHS Prototype Steering System

In order to utilize the ship's own steering system as much as possible, the EHS steering system was installed in the spare circuit of own steering system as shown in Figure 5. The valve A and B of EHS prototype are connected with valve A and B of conventional system.

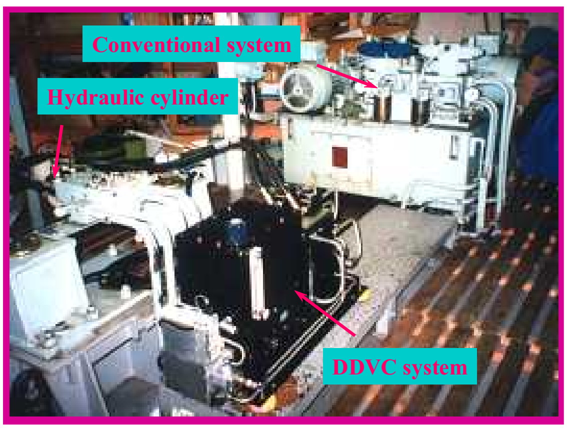
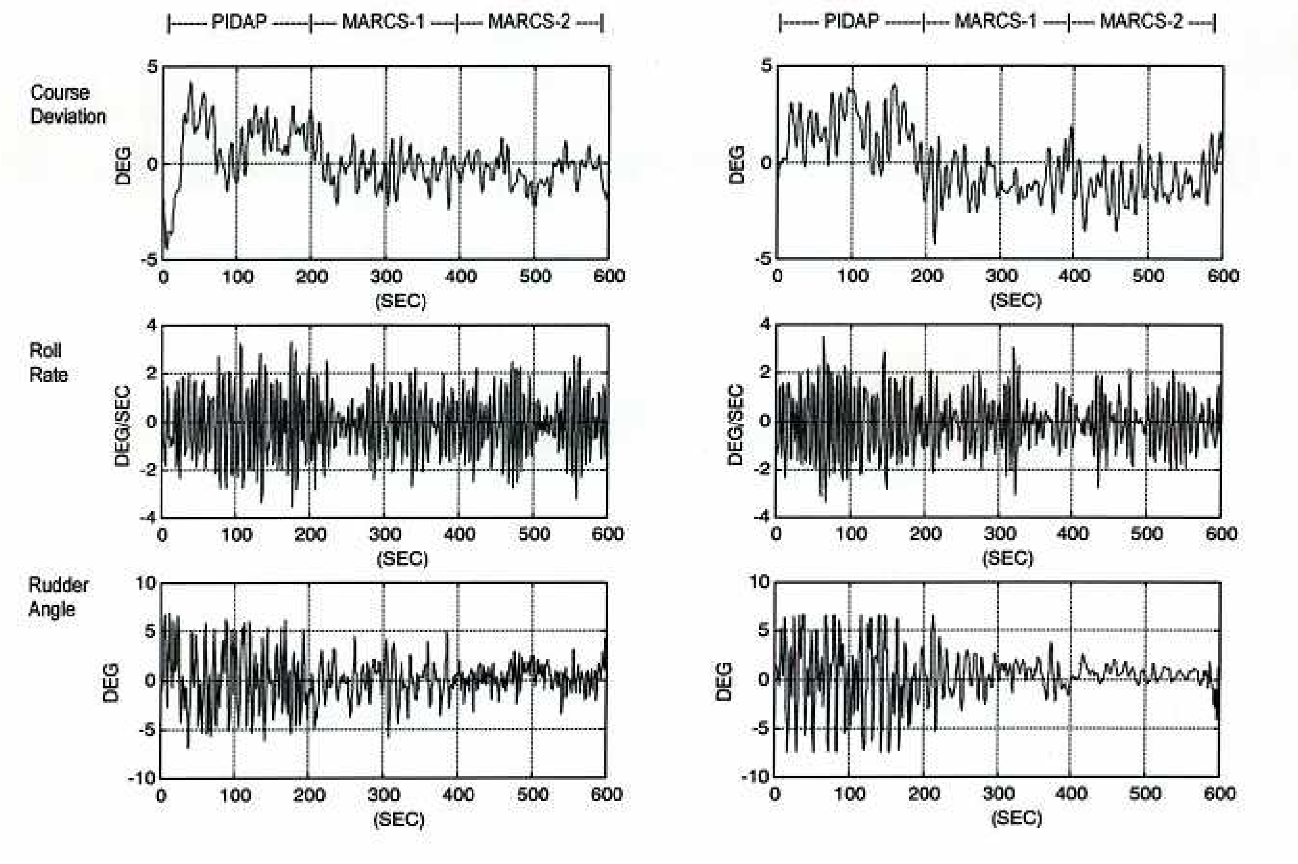


Figure 6 Conventional and EHS Steering System

The overview of steering room is illustrated in Figure 6. The EHS steering system is more efficient regarding size, weight, electric motor and oil tank volume in comparison with conventional steering system. Especially it understands that EHS steering system is excellent in term of slew rate. It would appear reasonable to assume that the cost of increasing the size and complexity of procurement of conventional system.

PERFORMANCE OF EHS STEERING SYSTEM

The authors carried out actual experiments aboard the training ship "SHIOJI MARU". Figure 6 shows the results of experiments of the batch adaptive MARCS. Figures on the left are the time series of ship course, roll rate, and rudder angle with the conventional steering system. Figures on the right are the time series of ship course, roll rate, and rudder angle with the EHS steering system.



Conventional Steering System (Ju32) **EHS Steering System (Ju35)**

Figure 6 Results of Adaptive MARCS
【Conventional and EHS Steering System】

There are three batch periods, each of which length is 200(sec) and the sampling time is 1.0(sec). The first batch shows result of the digital PID-typed steering law with disturbance. Both the second and the third batch period are the results of the rudder roll stabilization steering with MARCS. The batch adaptive MARCS uses the optimal gains adapting MARX model, which are estimated from the former batch data [6][7].
Table 4 shows the variances of ship course, roll rate, rudder angle and reduction ratios. The reduction ratios of roll rate are calculated by ship's auto-pilot and MARCS-1, MARCS-2 in the batch adaptive MARCS.
The reduction in the case of using EHS steering system is larger than that in the case of the conventional steering gear.
According to Figure 7 and Table 4, the authors can conclude that:
a. The rolling in the case of the MARCS using EHS is reduced less than that in the case of the conventional one.
b. When the weight function changed, the roll rate is reduced and a change in rudder motion is occurred simultaneously.

Table 4 Results of full scale experiments

Test No	Control Mode	Ship Course (Variance)	Roll Rate (Variance)	Roll Rate Reduction(%)
Ju32 (Conventional)	PIDAP	3.178266	2.525148	——
	MARCS-1	0.885640	1.291034	48.87
	MARCS-2	0.547671	1.535240	39.20
Ju35 (DDVC)	PIDAP	1.907401	2.218735	——
	MARCS-1	1.100737	1.063286	52.07
	MARCS-2	1.166585	0.945265	55.67

CONCLUSIONS

This paper presents the various stages of the design and development of advanced rudder roll stabilization system based high slew rate steering system and adaptive control. The effectiveness of any roll stabilization system depends on the magnitude of stabilization moment that is applicable to the ship. In order to make the MARCS more effective, it is necessary to improve a slew rate (rudder speed) design.
First, this paper introduced a high slew rate steering system with EHS. The EHS steering system realizes the

slew rate over 10(deg/s). The EHS has the advantage to save energy consumption on average by over 80(%) in comparison with a conventional hydraulic steering system. It was reported that the EHS steering system reduced the noise level about 10(dB) in comparison with the conventional one.
Next, this paper presented the application of the batch adaptive control based on a locally stationary auto-regressive model. The advanced MARCS reduced the roll motion in average with 30~50(%) comparison with the conventional autopilot. Through these studies, it proved that the EHS steering system and batch adaptive MARCS have higher controllability than the conventional MARCS for the problem of reducing roll motion of ships with rudder control.

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REFERNCES

1. H.Oda, K.0htsu, and T.Hotta
   Statistical Analysis and Design of a Rudder Roll Stabilization System. IFAC Control Eng. Practice, Vol.4. NO.3,1996.
2. H.Oda, KJgarashi, K.0htsu
   Simulation Study and Full Scale Experiment of Rudder Roll Stabilization System. llthSCSS,1996.
3. M.Ito, H.Sato, Y.Maeda
   Direct Drive Volume Control of Hydraulic System and its APplication to the Steering System of Ship. 5th Tech. Symp. on Fluid Control,1997.
4. K.0htsu, M.Horigome, G.Kitagawa
   A New Ship's Auto Pilot through a Stochastic'Model. Automatica, Vol.1, No.3, 1979.
5. H.Akaike
   On the use of a Linear Model for the Identification of Feedback systems. Ann. Inn. Statist. Math. Vol.20,1968.
6. T.Ozaki, H.Tong
   On the Fitting of NOn-Stationary Auto-regressive Models in Time Series Analysis. Proc. of 8th Hawaii Inter. Conference on System Science,1978.
7. K.0htsu, J.S.Park
   Batch Adaptive Rudder Roll Control System. J. Kansai Soc. N. A, Japan, NO.228,1997.