

# Genetic Algorithms for the Controller Design of Stabilization Fins

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## Summary

A fuzzy logic controller designed by genetic algorithms for a fin stabilizer system of ships is investigated. In the system, the roll angle and roll velocity of ships are chosen as the input variables of the controller to obtain the desired command for driving the active fins. The membership functions of the fuzzy sets for the input and output variables are determined by genetic algorithms. Some numerical simulations show the high efficiency of roll reduction by the stabilizing system with this controller for irregular wave load. The antiroll performance of present controller is better than ordinary fuzzy and classic controller. This system also performs well under free decay and steady wind load. Moreover, the efficiency of ship roll reduction will be kept for various ship speeds in this scheme.

## 1. Introduction

Roll has a significant effect on the discomfort of crew and passengers as well as cargo aboard ship. Some experimental data have shown that the roll motion can effect the ship's ability to maintain course and will increase resistance. Rolling also effects the landing of aircraft or helicopters on naval vessels. To contribute to a ship design more conducive to low roll, several pioneers have investigated the roll characteristic for different ship types by theoretical and experimental studies. In addition, some anti-rolling systems have been designed and installed on ships over the last one hundred or so years, such as bilge keels, gyroscopic stabilizers, moving weight stabilizers, antirolling tanks, rudder stabilizers and fin stabilizers<sup>(1),2),3)</sup>. Of these devices, fin stabilizer are by far the most effective roll reduction systems for middle and high speed ship. Thus, fin stabilizers have been widely installed on passenger liners, fast cargo liners, car ferries, and naval vessels<sup>(4)</sup>. The concept of a fins stabilizer system was first proposed for rolling reduction by Thornycroft in 1889. In the fins stabilizer system, more than one pair of

moving fins are installed symmetrically on the starboard and port side. The fins of the stabilization systems are usually turned by the hydraulic system, which is governed by the controller. When the ship rolls, the fins on the opposite side of the ship are turned in the opposite direction to generate a restoring couple to balance the roll motion shown in Fig. 1.

The fin geometry and the controller are two dominant factors which effect the efficiency of the fin stabilizer system. In general, the properly developed area, the aspect ratio and cross section area of fins are determined during fin geometry design to achieve sufficient lifting moment<sup>(5),6)</sup>. After the fin geometry was designed, the efficiency of the fin stabilizer system is predominantly dependent on the control action of the fins. For this reason, many control algorithms have been proposed for the fin stabilizer system in order to

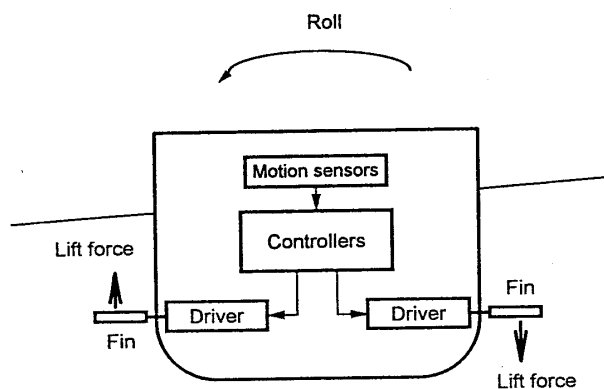


Fig. 1 Active fin stabilizer systems

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increase the efficiency of the system<sup>7),8)</sup>. In general, the dynamic model of the ship roll and fin stabilizer system should be accurately known if high efficiency of the roll reduction is the goal. However, this objective is very difficult to achieve because of the nonlinear and time variant characteristics of ship rolling. During the 1960s, Professor Zadeh had developed the theory of fuzzy logic<sup>9),10)</sup>. In recent year, the fuzzy controller has been successfully applied to several fields, such as control of cement kiln, water purification, train operation, robotics control, and autopilots for ships<sup>11)</sup>. The control law of the fuzzy controller can be determined by the expert's experience and engineering sense, and so, engineers are not pressed to accurately know the dynamics of the controlled object. In addition, this controller has good tolerance for model nonlinearity and time variant. Some results have shown that the fuzzy logic controller is suitable for the fin stabilizer system<sup>12)</sup>.

The efficiency the fuzzy logic controller depends on the membership functions of the input and output fuzzy sets and rule base. So, the key point of the controller design is to determine suitable membership functions and the rule base. Unfortunately, these functions can not be obtained by expertise or experience in the fins stabilizer system. It is also not easy to determine suitable membership functions and the rule base with high efficiency for roll reduction through an engineering knowledge. In this study, the genetic algorithms was applied to obtain the membership functions of the input and output variables and rule base for good performance. The genetic algorithms is an optimal search method based on the concept of natural evolution<sup>13)</sup>. This method has the property of eluding local mimimums. So global optimal design for the controller may be obtained if the number of generations is large enough. In the following example, the roll responses of a 1,500 ton ship under different sea states and steady wind load as well as free roll decay are analyzed to check the efficiency of the stabilizing fins with the designed controller.

## 2. Methods

### 2.1 Dynamics of motion

The motion of a ship advancing in a seaway is a complicated phenomenon due to the interactions between the vessel dynamics and distinct hydrodynamic forces. For convenience, the ship's motions are described by three translation components, surge, sway and heave, and three rotational components, roll, pitch and yaw. By the Newton's second law and coordinate transformation method, the equations of motion in the ship coordinate system can be derived as six coupled and nonlinear equations. After linearization, the general form of the equations of ship motion in six degrees of freedom is

$$\sum_{k=1}^6 \Delta_{jk} \ddot{\eta}_k(t) = F_j(t) \quad j=1, 2, \dots, 6 \quad (1)$$

where  $\Delta_{jk}$  are the components of the generalized inertia matrix for the ship,  $\ddot{\eta}_k$  are the translation accelerations or angular accelerations in the degree of freedom  $k$ ,  $F_j$  is the total force or moment action on the ship in direction  $j$ . The motion with respect to the degree of freedom 1, 2, ..., 6 are surge, sway, heave, roll, pitch and yaw. For the usual case of a ship with port starboard symmetry, the six coupled equations can be reduced to two sets equations, the equations for vertical plane motions, surge, heave and pitch, and the equations for horizontal plane motions, sway, roll and yaw. Thus, the roll motion of ships is dependent not only on the forces of wave and wind but also on the motions of sway and yaw. Since the linearization is applied for deriving dynamic equations, Eq(1) is only suitable for small ship motion. However, the roll response may not be small if the ship is not in moderate sea states. Large roll motion can be derived from the law of conservation of energy. The energy given by the waves wind and other excitation loads is equal to the sum of the kinetic and potential energy of roll motion, and exhaust heat caused by damping. From the experimental tests of models and measurement results of real ships<sup>14),15)</sup>, the rolling response can be expressed as a time variant nonlinear differential equation such as

$$I(\eta_4, t) \ddot{\eta}_4 + C(\dot{\eta}_4, \dot{\eta}_4^2, \dots, t) + K(\eta_4, t) = M_{\eta_4}(\eta_4, t) \quad (2)$$

where  $I$  is the mass moment of inertia of the ship in water for rolling,  $C$  is the damping moment,  $K$  is the restoring moment, and  $M_{\eta_4}$  is the total excitation moment. The mass moment of inertia is the integration of the moment of inertia of each part of the ship body and cargo. The added mass moment of inertia depends on the shape of the ship and the relative motion between the ship and wave. The damping moment is due to the eddy making force of the bilge keel and appendages below the water line, the wave generating force by ship motion, the water friction on the ship surface, and air resistance on the superstructure and ship body. It is very difficult to calculate the damping moment by theoretical analysis. However, several experimental tests were proposed to estimate that. The restoring moment of a ship for rolling is the righting moment at inclination. For a small roll angle, the restoring moment is proportional to the rolling angle. However, the restoring moment will be increased for large roll angles due to the increment of the metacentric height.

If pairs of fins installed on the ship are considered, the total excitation moment will include the external moment and the active moment expressed as

$$M_{\eta_4}(\eta_4, t) = M_e(\eta_4, t) + M_{fin}(\eta_4, t) \quad (3)$$

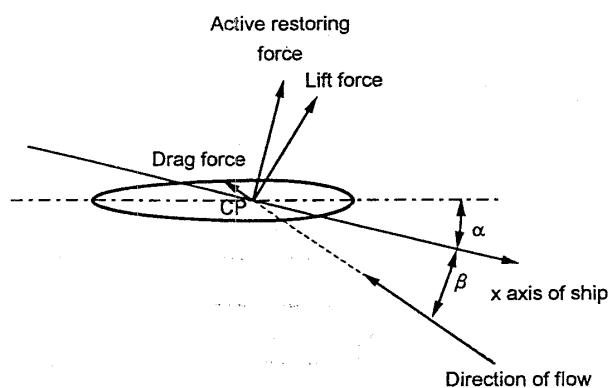
where  $M_e(\eta_4, t)$  is the external moment, which is induced by the wind and wave loads, ship turning, mass movement on the ship, and fluid excitation in the tanks. In general, the wind and waves are the dominant excitation sources. Thus  $M_e(\eta_4, t)$  is a function of wind speed, wind direction, wave slope and wave direction. Since

the parameters of the wind and the waves are random and unpredictable, the external moment should also be random and nondeterministic.  $M_{fin}(\eta_a, t)$  is the active moment, which is generated by the fins. In general, a symmetric cross section and all-movable surfaces are selected to offer a symmetric opposite moment for opposite tilt. The active moment created by the fins is given by

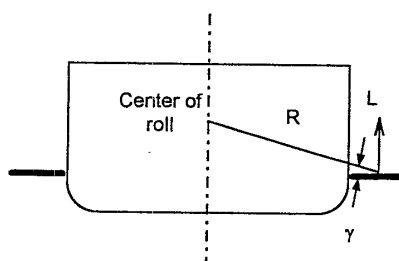
$$M_{fin}(\eta_a, t) = \sum_{i=1}^n \frac{1}{2} \rho A_{fi} V_{fi}^2 \left( \frac{dC_L}{d\alpha} (\alpha_i + \beta_i) \cos(\beta_i) + \frac{dC_D}{d\alpha} (\alpha_i + \beta_i) \sin(\beta_i) \right) D_i \cos(\gamma_i) \quad (4)$$

where  $\rho$  is the density of water,  $A_{fi}$  is the area of the fin,  $V_{fi}$  is the relative velocity of fins to flow,  $\frac{dC_L}{d\alpha}$  is the slope of the lift curve,  $\frac{dC_D}{d\alpha}$  is the slope of the drag curve,  $\alpha_i$  is the angle of fin tilt, and  $\beta_i$  is the angle between fin movement direction and the x axis of ship,  $R_i$  is the distance along a line from the roll center to the lifting center of the fin, and  $\gamma_i$  is the angle between the fin axis and this line as shown in Fig. 2. Due to the hull boundary layer, the velocity of fins with respect to flow is slower than the ship speed. In addition, the relative velocity and direction of input flow will be effected by other disturbances, such as current, wave, and ship rolling

The fins are driven by a hydraulic servo system, which includes the hydraulic supply, servo valve, cylinder, and mechanism. Since the torque required for stabilizing fins is large, the characteristics of this system will be low response and highly nonlinear. For



(a) Fin force components



(b) Location of fins

Fig. 2 Force generation and location of fins

simplicity, a one degree differential equation with time lag is usually used for system design, given by

$$\tau \dot{\alpha}(t) + \alpha = k_h \nu_a(t - t_d) \quad (5)$$

where  $\tau$  is the time constant,  $k_h$  is the gain constant,  $\nu_a$  is the control command, and  $t_d$  is the time lag of the hydro-servo system.

### 2.2 Fuzzy logic controllers

The fuzzy logic controller is operated by the fuzzy logic sets theory. Fuzzy logic looks at the word in imprecise term, in which the same way that our own brain takes in information. Fuzzy logic is different from classical two-value logic. In classical two-value systems, all classes are assumed to have sharply defined boundary. But most classes in the real word do not have sharp boundary. So fuzzy logic was developed to represent and reason some particular form of knowledge. The fuzzy controller consists of four parts; the fuzzification component, the rule base, the inference engine, and the defuzzification component. The principal structure of a fuzzy logic controller is shown in Fig. 3.

The function of the fuzzification component is to map the physical values of the current process input variables into a fuzzy-set. If a fuzzy set  $F$  is defined on the universe  $U$ , for any element  $u$  of  $U$ , the membership function of a fuzzy set  $F$  is expressed as

$$\mu_F : U \rightarrow [0, 1] \quad (6)$$

For every element  $u$  of  $U$ , the membership degree is defined in the range between 0 and 1 described as  $\mu_F(u) \in [0, 1]$ . The fuzzy set  $F$  is determined by

$$F = \{(u, \mu_F(u)) | u \in U\} \quad (7)$$

For example, the fuzzy set may be chosen as positive, zero or negative for force, or large, middle, small for house size.

Several types of membership functions have been proposed, such as the triangular type, the exponential type, the bell shape type and the trapezoid type. In these types, the triangular membership function is the most commonly used because the fuzzification and defuzzification processes are simple.

The base function of the rule base is to represent the control policy of an experienced process operator or control engineer in the form of a set of rules such as "if  $\langle \dots \rangle$  then  $\langle \dots \rangle$ ". The if part of such a rule, called the rule antecedent, is a description of a process input variable in terms of a logical combination of fuzzy

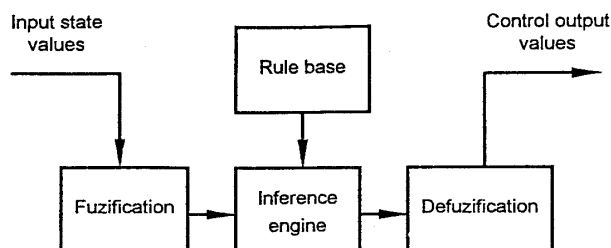


Fig. 3 The structure of the fuzzy logic controller

propositions. The *then* part of the rule, called rule consequent, is again a description of the control output in terms of logical combination of fuzzy propositions. These propositions represent the linguistic values which the control output variables take whenever the current process input state matches the process input state description is the rule antecedent. Let us consider a fuzzy controller, which has two process input variables  $x_1$ ,  $x_2$  and one control output variable  $y$ . Then the rule included in the rule base can be written in the form

$$\text{Rule}(k): \text{if } x_1 \text{ is } X_1^{(k)} \text{ and } x_2 \text{ is } X_2^{(k)} \text{ then } y \text{ is } Y^{(k)} \quad (8)$$

where  $X_1^{(k)}$  and  $X_2^{(k)}$  are the input fuzzy sets,  $Y^{(k)}$  is the output fuzzy set. For easy operation, these rule bases may usually be described as a matrix structure in controller design.

The inference engine is used to calculate the controlled values based on the composite rules of inference. The inference engine can be of two basic types, composition based inference and individual rule based inference. In the first type, the fuzzy relations of each individual rule are aggregated into one fuzzy relation of the overall set of rules. Then, the inference with this fuzzy relation is performed via the operation composition between the fuzzified input and the fuzzy relation of the overall set of rules. In the second type, each single rule is processed individually. Firstly, the degree of match between the input and the fuzzy sets of the rule antecedent is computed. Then, clipping the fuzzy set of the rule consequent to the degree to which the rule antecedent has been matched by the fuzzified input. Finally, the clipped values for the control output of each rule are aggregated to form the value of the overall control output. Usually, the second type of the inference is preferred since it is computationally very efficient and saves a lot of memory. In the case of the individual rule based inference the overall control output may be obtained by the *AND* and *OR* operation as

$$\forall u: \mu_Y(y) = \bigcup (\bigcap (\mu_{X_1^1}(x_1^*), \mu_{X_2^1}(x_2^*)), \mu_{Y^1}(y)), \dots, \bigcap (\bigcap (\mu_{X_1^n}(x_1^*), \mu_{X_2^n}(x_2^*)), \mu_{Y^n}(y)) \quad (9)$$

where  $\bigcap$  and  $\bigcup$  are the *AND* and *OR* operator,  $\mu_{X_i^k}(x_i^*)$  is the degree of membership of the fuzzified input  $x_i^*$  in  $\mu_{X_i^k}$ . A correlation-minimum function is commonly used for the *AND* operation and correlation-maximum function for *OR* in calculation.

The defuzzification component performs the inverse operation of fuzzification and is used to transfer the decision results into a countable output. Many methods have been used in defuzzification, such as center of area method, center of sums method, height method, center of largest area method, middle of maxima method and etc. Of these methods, the center of area method is the best well known defuzzification method. In the continuous case system, the center of area method is expressed as

$$u^* = \frac{\int_U u \cdot \mu_U(u) du}{\int_U \mu_U(u) du} \quad (10)$$

### 2.3 Genetic algorithms

Genetic algorithms were invented to simulate some of the processes observed in biological evolution. In nature, the biological evolution is driven by the survival of the fittest. The stronger living being tends to survive longer and bear many offspring, while the weaker one become extinct. The genetic algorithms can generally be characterized by the steps of initial population, evaluation, parent selection, reproduction, and mutation. A flow chart description of the genetic algorithms is contained in Fig. 4.

The purpose of the genetic algorithms is try to find the optimal individual with minimal performance function. The characteristic of each individual is completely determined by the chromosome, which is a collection of primitive features called genes. Before processing the genetic algorithms, the parameter of the performance function to be minimized should be encoded as genes in a chromosome. Initially, the individual is randomly generated to create the population pool. In the evaluation step, the performance function values is calculated from the chromosome. The performance function value is also converted to fitness, which is a measure of how well a chromosome performs. Since the goal is to minimize the performance function, poor fitness implies a large performance function value. The fitness is used to determine the frequency of the individual to be chosen as parent. In general, the higher the individual fitness is, the higher the selection probability is. Two parents are chosen from the population pool to generate children.

In the reproduction step, some genes of the chromosome in both parents are used to generate two children. In general, a crossover point along the chromosome is

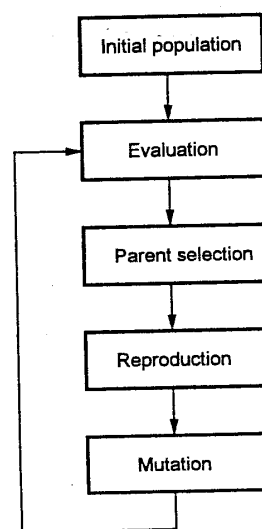


Fig. 4 Computation procedures of the genetic algorithms

randomly selected. The chromosomes of both parents will be split at this point. Half of the genes on one side of this point in one parent will be given to the first child. The other half of the genes of the first child will come from the other side of the crossover point in the other parent. After generating the first child, the residual genes of both parents are combined to create the second child. Mutation plays an important role in genetic optimization. It introduces new genetic material into the population pool. Proper mutation will create a good chromosome, which will overcome the insufficient population pool. Some inferior genes may also be introduced into the pool by incorrect mutation. To avoid capricious destruction in the gene pool, the probability of mutation should be constrained to a small value.

In the design of the fuzzy logic controller, the membership functions of input and output variable, and the rule base are the important functions to be adjusted by the genetic algorithms. In the implementation, these functions should be expressed by some characteristic parameters. Then these parameters are transferred to the code of the gene and chromosome. In addition, the performance function plays an important role in the genetic algorithms. The performance function is defined to express the fitness of the design objective. A simple criterion for the stabilizers system can be designed as the integration of the absolute value of the roll error which is the angle between the actual roll response and the upright direction.

3. Results

A 1,500 ton ship was chosen as the example to illustrate the performance of the controller designed by the genetic algorithms. A pair of *NACA 0015* section rectangular fins with area 2 m<sup>2</sup> are chosen for roll stabilization in the ship. The distance between the lifting center of the fins and the rolling center is 6.8 m. The line from the roll center to the lifting center and the fin rotation axis is collinear. Both fins are driven by a hydraulic servo system, in which the time constant is 0.1 sec. The tilt of fins is constrained under 40 deg to avoid their tilt over the stall angle and cavitation range. The regular ship speed is 20 kt.

In the controller, the roll angle and roll rate of ship are chosen as the input linguistic variables. The fuzzy sets for both input variables are defined as *PL*: "positive large", *PM*: "positive medium", *PS*: "positive small", *ZE*: "zero", *NS*: "negative small", *NM*: "negative medium", and *NL*: "negative large". The triangular membership functions is chosen for each fuzzy set. The rule base is determined through a sense of general control engineering. If the response of roll is divided into four phases, it would be very easy to assign an action at a certain point in each phase in order to improve the response. The, the control rule can be obtained and listed in matrix stucture show in Fig. 5. The membership function for each fuzzy set is generat-

ed by the genetic algorithms. Three sets of arbitrary initial membership functions are given for genetic algorithms shown in Fig. 6. Those membership functions are governed by the control points *C*<sub>11</sub>, *C*<sub>12</sub>, *C*<sub>13</sub>, *C*<sub>21</sub>, *C*<sub>22</sub>, *C*<sub>23</sub>, *C*<sub>31</sub>, *C*<sub>32</sub> and *C*<sub>33</sub>. So, we can adjust those control points to get different membership functions. Each control point value is coded as a 32 bits gene. The condition of the irregular sea state 7 in the beam sea are considered for controller design. The wave spectrum of the wave motion is based on the International Towing Tank Conference (ITTC) spectrum formulation<sup>2)</sup>. In the calculation, the number of individuals in the population is 60. The probability of crossover is 0.8. The

Roll Velocity	Roll Angle						
	PB	PM	PS	ZO	NS	NM	NB
PB	NB	NB	NB	NB	NM	NS	ZO
PM	NB	NB	NB	NM	NS	ZO	PS
PS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
NS	NM	NS	ZO	PS	PM	PB	PB
NM	NS	ZO	PS	PM	PB	PB	PB
NB	ZO	PS	PM	PB	PB	PB	PB

Fig. 5 Linguistic matrix of the rule base

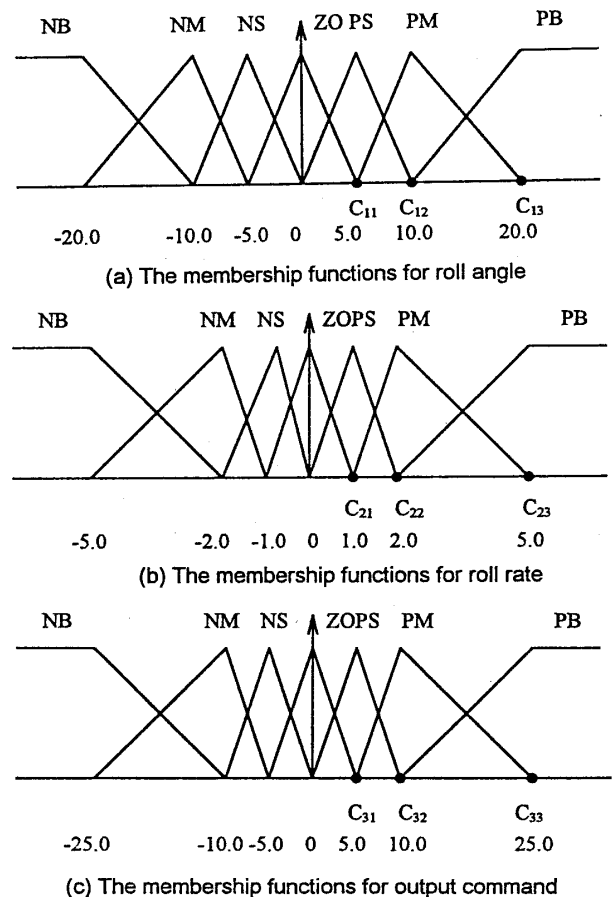


Fig. 6 The initial membership functions for the controller

probability of mutation is 0.1%. The total number of generation is 300.

Fig.7 shows the membership function for each fuzzy set obtained by the genetic algorithms. We examined some cases to understand the performance of this controller, based on the calculated membership functions and the rule base assigned. The first case studied was the irregular wave load. Assume that the conditions of the sea state 7, ship speed 20 kt in beam sea are considered. The wave history is shown in Fig. 8(a). Fig. 8(b) is the roll response of the ship without using fins. We found that the average amplitude of roll angle is 3.5 deg and the maximum peak to peak roll angle is 23 deg. When the designed controller is installed, the roll response will be reduced significantly as shown in Fig. 8(c). The average amplitude of roll is decreased to 0.3 deg and the maximum peak to peak value is less than 1.5 deg. The tilt angle of the fin is shown in Fig. 8(d). To compare the results of the present scheme, the performance of an ordinary fuzzy control system and classic control system are computed at the same sea load. Fig.9 shows the roll response controlled by ordinary fuzzy control system with the membership functions and fuzzy rule base shown in Figs. 6 and 5. Fig. 10 is the response of ship, which has PD controller with  $K_p=2.4$  and  $K_d=4.2^{16}$ . These results show the antiroll performance of the stabiliz-

tion fins driven by ordinary fuzzy and classic control system is obvious lower than that of the fins by the fuzzy control system design by genetic algorithms.

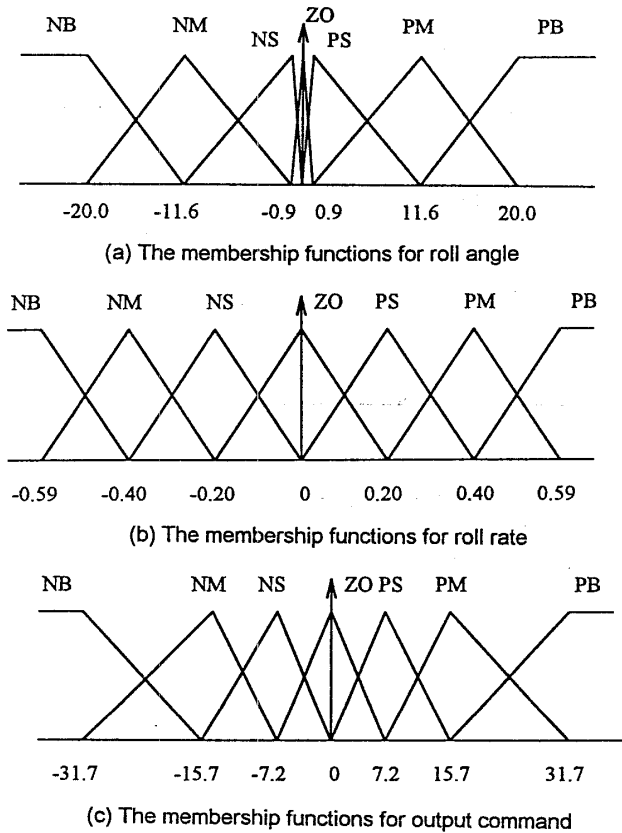


Fig.7 The membership functions designed by genetic algorithms

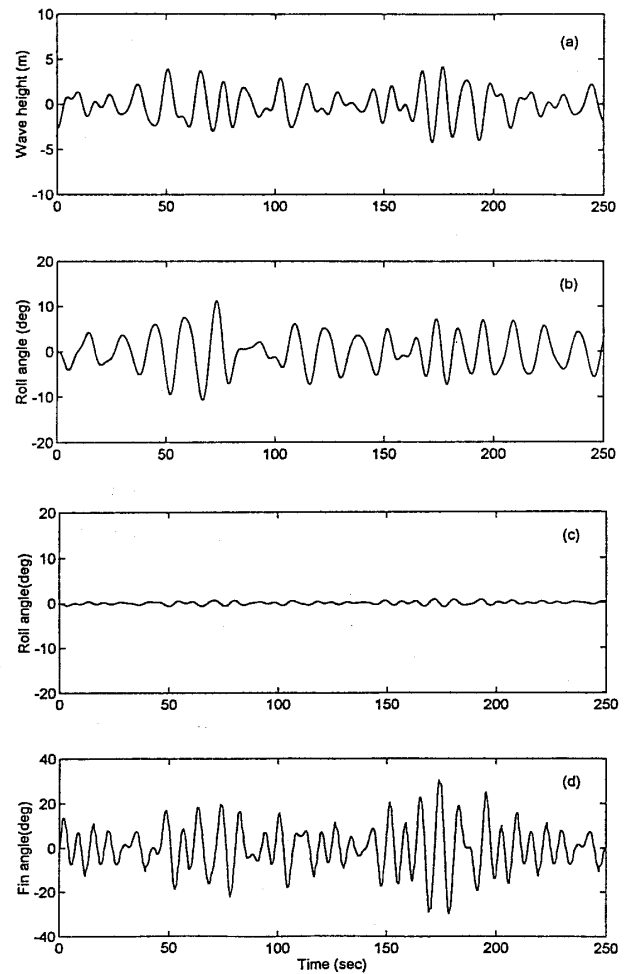


Fig.8 Load and response of the ship at sea state 7 (a) wave height (b) unstabilized roll (c) stabilized roll (d) fins angle

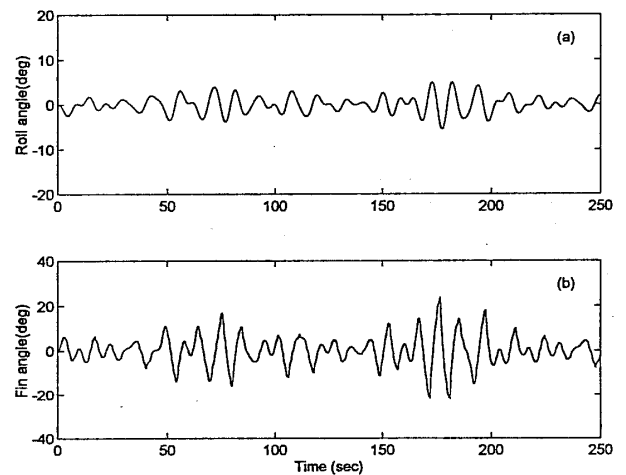


Fig.9 Load and response of the ship with ordinary fuzzy controller (a) roll response (b) fins angle

Figs. 11 and 12 show the roll response of unstabilized and stabilized cases in sea state 6 and 5. The results indicate that the rolling response of the ship is also reduced significantly by the fin stabilizer system. The effectiveness of the stabilizers design by this scheme at

sea state 5, 6 and 7 is more than 90%. In addition, we know the lift force generated by the fins would be decreased if the ship speed is slowed down. So it is important to check the efficiency of the stabilizers at a lower speed. Fig. 13 and 14 are the stabilized roll

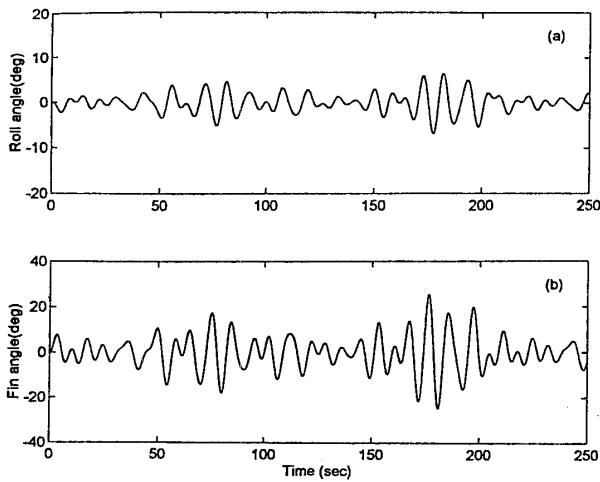


Fig. 10 Load and response of the ship with PD controller (a) roll response (b) fins angle

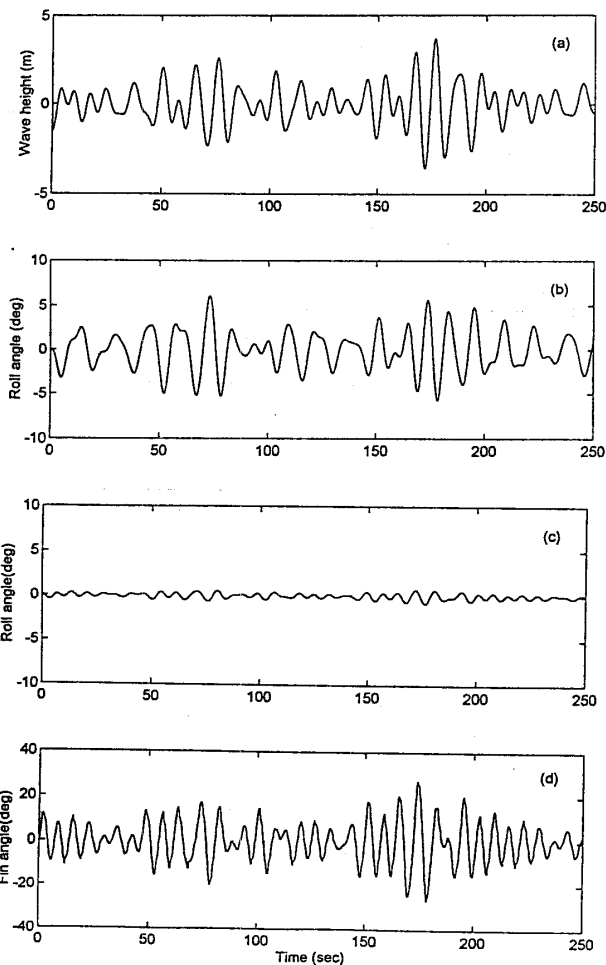


Fig. 11 Load and response of the ship at sea state 6 (a) wave height (b) unstabilized roll (c) stabilized roll (d) fins angle

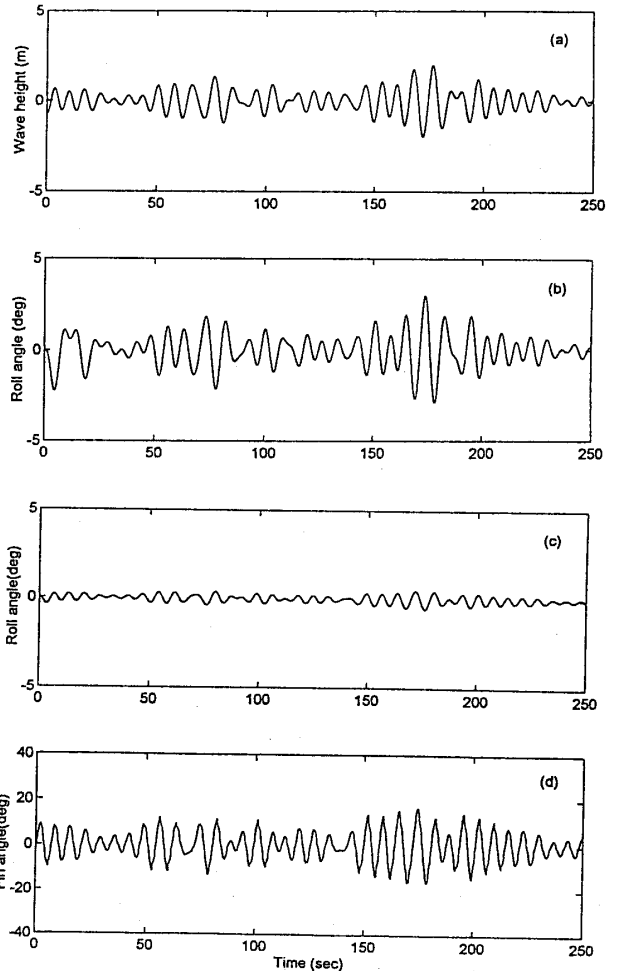


Fig. 12 Load and response of the ship at sea state 5 (a) wave height (b) unstabilized roll (c) stabilized roll (d) fin angle

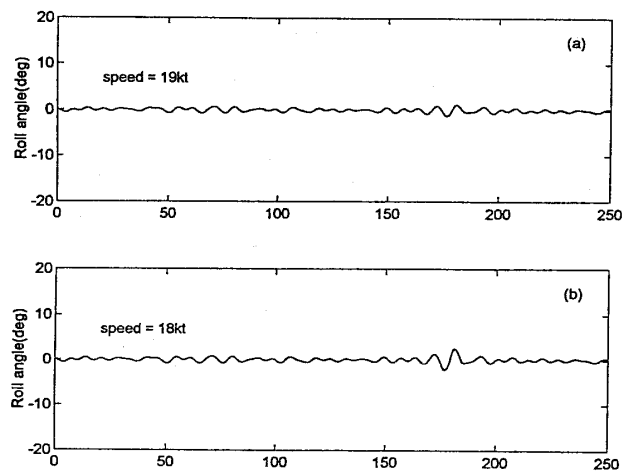


Fig. 13 Roll response of stabilized ship at sea state 7 (a) ship speed 19 kt (b) ship speed 18 kt

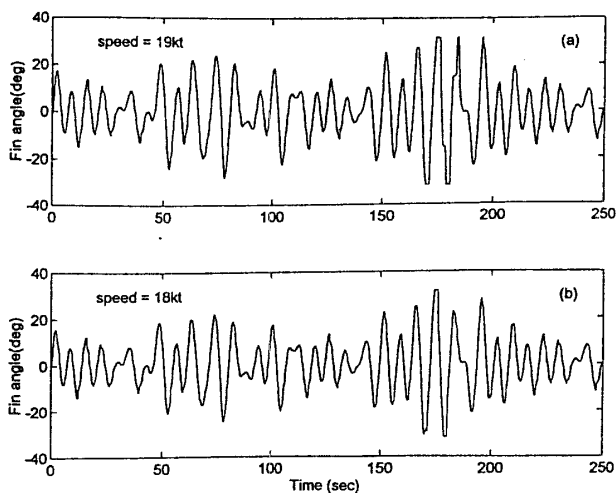


Fig. 14 Fin action of stabilizers at sea state 7 (a) ship speed 19 kt (b) ship speed 18 kt

response and fin tilt angle at ship speed 19 or 18 kt. The results show most of the roll response in the stabilized case can be kept at the same level even when the ship velocity is at a slower speed. We also see that the effect of the stabilizer is limited at a slow ship speed if the maximum lift moment cannot cover the excitation load such as the response between 160 sec to 200 sec in Fig. 13.

Free decay is a common test condition to identify the roll characteristics. Assume that the initial conditions of the ship are roll angle 10 deg and zero roll velocity. Fig. 15 shows the response of the ship without stabilization fins is an oscillation, which will be eliminated efficiently by the stabilization fins. In addition, an excitation moment of 50 ton-m step function modeling a steady wind load is considered in the second case. The heel angle of the ship will be 5.5 deg after a transient oscillation if the ship does not have fins. The ship heel can be restored to only 2 deg without oscillation by the fin stabilizer system. The steady state of fins tilt is 9 deg as shown in Fig. 16.

#### 4. Conclusions

A design of a fuzzy logic controller for a fin stabilizer system to reduce rolling using genetic algorithms has been investigated. To demonstrate the performance of the fin stabilizer system with this controller, the cases of the irregular wave load, sea state 5, 6 and 7 are studied. We see that effectiveness of the roll reduction by the designed controller is more than 90% in these sea state. The results also show the antiroll performance of present controller is better than ordinary fuzzy and classic controller. In addition, the controller can also automatically compensate the lift moment to keep the efficiency of stabilizers when the ship speed is slowed down. The free decay response shows that the roll characteristics is improved to avoid oscillation by this controller. From the example of steady wind load, we

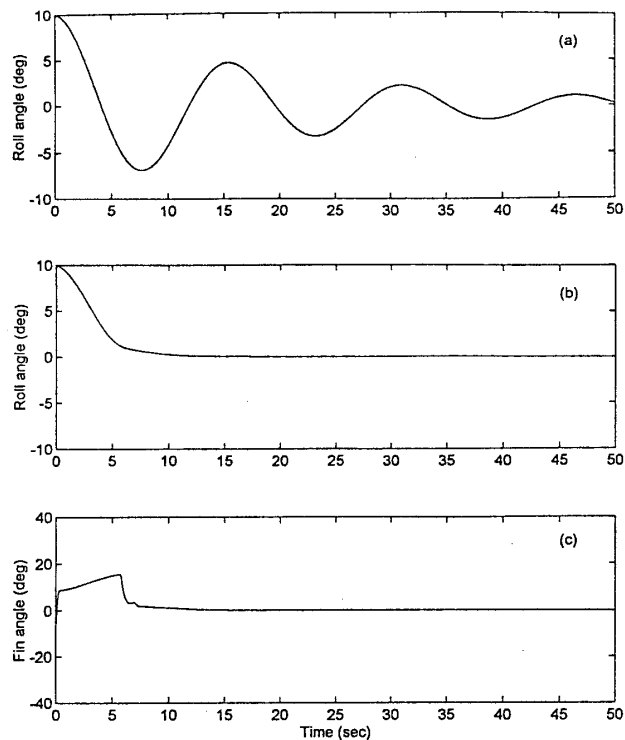


Fig. 15 Free decay response (a) unstabilized roll (b) stabilized roll (c) fin angle

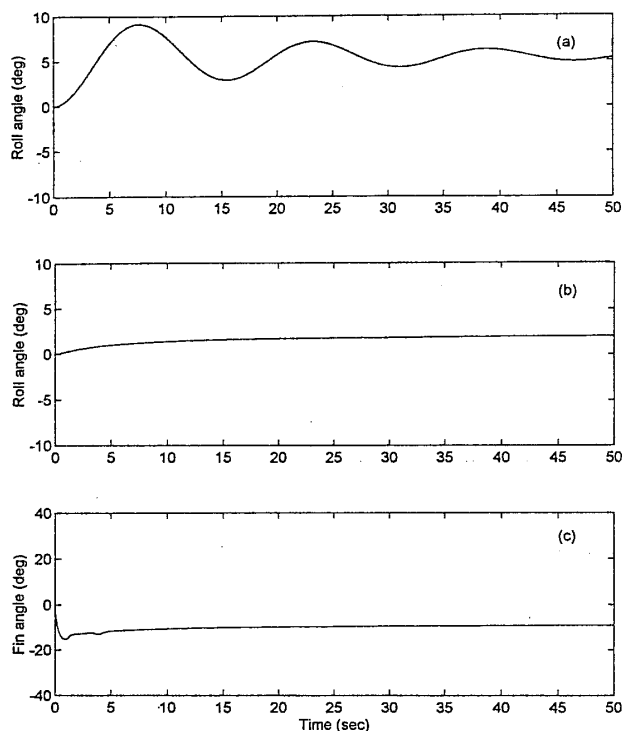


Fig. 16 Steady wind load response (a) unstabilized roll (b) stabilized roll (c) fin angle

also find this controller can offer a steady moment to reduce the load.

Although the feasibility of the scheme has been shown in this paper, more advanced study should be conducted along with further experiments to verify the

reliability of the stabilizers system.

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