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An Investigation on the Ship Rudder with Different Control System

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Introduction

Ships are faced with disruptive impacts because of their hydrodynamic environments. Automatic control systems are used in ships for routa controlling; tracking and balancing of drift and roll motions. To control these system proportional (P), proportional-derivative (PD) and proportional-integral-derivative (PID) and fuzzy logic (FL) control systems have been developed. So these disruptive impacts can be removed by controllers.

An auto pilot is used generally in ships and the block diagram is the autopilot shown in Figure 1. The aim of using this kind of control system in ships is to make drift and roll angles act the right way by using rudder and roll balancing systems.

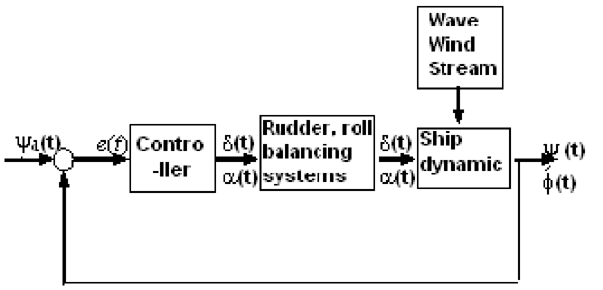

Fig. 1. Block diagram of drift and roll balancing system

Dynamic model and dimensions of chemical tanker

The dynamic model has been formed considering the real parameter such as crusing speed, angle etc. and physical dimensions of chemical tanker. In other studies, mathematical model of ship motions has been described with Newton mechanics based on SNAME (The Society of Naval Architects and Marine Engineers) notation.

Piloting, drifting and swaying motions describe the location of ship and heaving, pitching and rolling are the motions against external forces that hit the balance of ship., The motion status which has six degrees of freedom is given In Fig. 2 by considering SNAME notation.

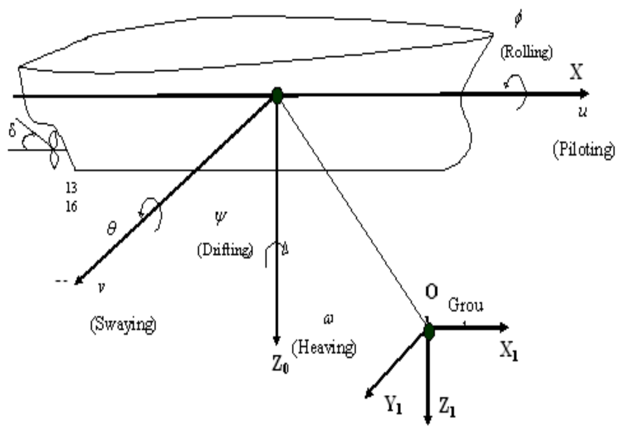

Fig. 2. The relationship between ship body and ground reference axis according to SNAME notation

Ship motion notations have been collectively given in Table-1.

Table 1. Ship motion notations [1].

	Motions	Force & Momentum	Velocities	Loca-tions
1	Piloting	X	u=dx/dt	x
2	Swaying	Y	u=dy/dt	y
3	Heaving	Z	u=dz/dt	z
4	Rolling	K	u=dϕ/dt	ϕ
5	Pitching	M	u=dθ/dt	θ
6	Drifting	N	u=dψ/dt	ψ

Locations $[x\ y\ z]^T$ and $[\phi\ \theta\ \psi]^T$; linear velocities $[u\ v\ w]^T$ and angular velocities $[p\ q\ r]^T$; respectively forces and torques $[X\ Y\ Z]^T$, $[K\ M\ N]^T$ are described according to axis system fixated to body[1].

It has been assumed that ship is piloting in calm waters. Motion equations that have six degrees of freedom can be degraded to motion that has three degrees of freedom (drifting, rolling and swaying) by assuming followings:

- Moving centre of gravity to point 'O', $r_G = [0,0,0]^T$;
- Homogeneous mass transfer on $X_0 Z_0$ symmetry plane, $(I_{xy} = I_{yz} = 0)$;
- If heaving, Rolling and pitching modes are neglected, $(w = p = q = \dot{w} = \dot{p} = \dot{q} = 0)$.

So ship motions that have three degrees of freedom are described depending on terms of location, velocity and acceleration.

Swaying:

$$(m - Y_{\dot{v}})\dot{v} = Y_v v + Y_\phi \phi + Y_p p + Y_{\dot{p}} \dot{p} + Y_r r + Y_{\dot{r}} \dot{r} + Y_\delta \delta \cdot \quad (1)$$

Rolling:

$$(I_x - K_{\dot{p}})\dot{p} + W\,GM\,\phi = K_p p + K_v v + K_{\dot{v}} \dot{v} + K_r r + K_{\dot{r}} \dot{r} + K_\delta \delta \,. \quad (2)$$

Drifting:

$$(I_z - N_{\dot{r}})\dot{r} = N_r r + N_\phi \phi + N_p p + N_{\dot{p}} \dot{p} + N_v v + N_{\dot{v}} \dot{v} + N_\delta \delta \,. \quad (3)$$

The constant of Laplace Transform function of Eqs. 1, 2, 3 are given in Table-2 in order to find transfer functions drifting, rolling and swaying which is depended rudder angle.

Table 2. a, b and c constants

$a_1 = (m - Y_{\dot{v}})s - Y_v$	$b_2 = K_{\dot{v}} s + K_v$	$c_1 = (I_z - N_{\dot{r}})s - N_r s$
$a_2 = Y_{\dot{p}} s^2 + Y_p s + Y_\phi$	$b_3 = K_{\dot{r}} s + K_r$	$c_2 = N_{\dot{v}} s + N_v$
$a_3 = Y_{\dot{r}} s + Y_r$	$b_4 = K_\delta$	$c_3 = N_{\dot{p}} s^2 + N_p s + N_\phi$
$a_4 = Y_\delta$		$c_4 = N_\delta$

Drifting angle 'ψ', rolling angle 'ϕ' and swaying velocity 'v' are obtained as follows [2] after neglecting swaying velocity 'v' , relation between rudder angle 'δ' and respectively.

$$G_1 = \frac{\psi}{\delta} = \frac{a_1(b_1c_4 + b_4c_3) + a_2(b_4c_2 - b_2c_4) + a_4(b_1c_2 + b_2c_3)}{a_1(b_1c_1 - b_3c_3) - a_2(b_2c_1 + b_3c_2) - a_3(b_1c_2 + b_2c_3)}, \quad (4)$$

$$G_2 = \frac{\phi}{\delta} = \frac{[(a_3c_1 - a_1c_3)G_1 + (a_4c_1 - a_1c_4)]}{-(a_2c_1 - a_1c_2)}, \quad (5)$$

$$G_3 = \frac{v}{\delta} = \frac{[(a_2c_3 - a_3c_2)G_1 - (c_4a_2 - a_4c_2)]}{(a_1c_2 - a_2c_4)}. \quad (6)$$

Term of 'WGM' in (1. b) is balancing rolling moment

$$W\,GM = \rho g \nabla GZ(\phi), \quad (7)$$

where '∇' – displacement; 'g' – gravitational constant; 'ρ' – sea water density; '$GZ(\phi)$' – rectifier torque function are as follows at very small angles [3],

$$GZ(\phi) = GM \sin\phi, \quad (8)$$

where GM is metacentre height; BM is distance between met centre and underwater mass centre. In this application, the dynamic model has been obtained considering the actual parameter and physical dimensions of chemical tanker [4-12].

Table 3. Dimensions of chemical tanker

	Sym.	Value	Unit
Length from head to rudder	L	108.010	m
Maximum width	B	16	m
Design draught	T	6	m
Displacement	W	7945	ton
Nominal velocity	U	14	m / s
Meta centre height	GM	0.744	m
Fullness ratio		0.747	
Rudder area	A_R	8	m^2
Rudder angle	δ_{max}	35	der.
Rudder velocity	$\dot{\delta}_{max}$	2.3	der/s

Control of ship drifting motion

In this part, drifting motion of chemical tanker that has one degree of freedom is going to be controlled using PD, PID and fuzzy logic methods. The purpose of autopilot's control is to keep drifting angle constant in any event. Ship's motion that has one degree of freedom is expressed with second order Nomoto model. Criterions of behaviour in application can be selected as follows [13]:

- Drifting velocity 0.25 deg/s;
- Overshoot $\leq$ % 20.

For the unit step response, drift motion of ship must be controlled by improving system damping rate and overflow. Controllability of our system should be investigated before starting to control. For being drifting motion expressed in state space form controllable, rank of following controllability matrix -whose dimension is (n x nr)- must be 'n' [14].

When we form controllability matrix of this model, we see that the rank of the matrix is equal to two

PID Control of ship drifting motion

Main design target of PID controller is to calculate K_p, K_d ve K_i control coefficients and arrange them to provide performance conditions of given closed loop system. In this application, PD and PID control methods have been applied to control drifting motion of chemical tanker. The target is controller's effective catching of reference value as soon as possible.

Table 4. Effects of PID gaining's on performance changing

Controller	Rising Time	System sudden response	settling Time	Status Error
K_p	Decreases	Increases	Changes little	Decreases
K_i	Decreases	Increases	Increases	Eliminates

Controller	Rising Time	System sudden response	settling Time	Status Error
K_d	Changes little	Decreases	Decreases	Changes little

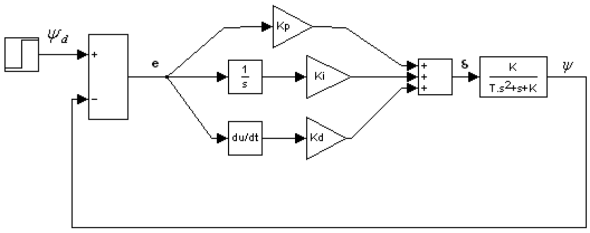

Fig. 3. PID Control block diagram of drifting motion

PID controlled rudder dynamic is expressed as,

$$\delta = K_p\, e + K_d\, \dot{e} + K_i \int_0^t e\, dt\,, \tag{9}$$

where '$\delta(t)$' is rudder control signal; '$e = (\psi_d - \psi)$' is amount of error; 'K_p' is proportion constant; 'K_d' is derivative constant and 'K_i' is integral constant. $K_p > 0$, $K_d > 0$ and $K_i > 0$ controller coefficient must be positive. When it is replaced in equation (11) by neglecting integral gain in expression (9):

$$T\ddot{\psi} + \dot{\psi} = K(\delta - \delta_0)\,, \tag{10}$$

$$T\ddot{\psi} + \dot{\psi} = K\left[K_p(\psi_d - \psi) + K_d(\dot{\psi}_d - \dot{\psi})\right]. \tag{11}$$

PD controlled Nomoto equation is obtained. Here, derivative of reference value is equal to zero, when 'δ_0', angle of rudder deviation is adjusted to starting value-zero. To find control gain, ship dynamic and proportional-derivative controllers are expressed as follows

$$T\ddot{\psi} + (1 + KK_d)\dot{\psi} + KK_p\psi = K K_p \psi_d\,. \tag{12}$$

By making this equation eligible for second order system

$$\ddot{\psi} + 2\xi\,\omega_n\dot{\psi} + \omega_n^2\,\psi = \omega_n^2\,\psi_d\,. \tag{13}$$

Control constant are showed depending on natural frequency 'ω_n (rad/s)' and damping proportion 'ξ' .

$$\begin{cases} K_p = \dfrac{T\,\omega_n^2}{K}, \\ K_d = \dfrac{2T\,\xi\,\omega_n - 1}{K}. \end{cases} \tag{14}$$

When PID control is applied to Nomoto equation:

$$T\ddot{\psi} + \dot{\psi} = K\left[K_p + K_d\, s + K_i \frac{1}{s}\right](\psi_d - \psi)\,, \tag{15}$$

$$T\sigma^3 + (1 + KK_d)\sigma^2 + KK_p\sigma + KK_i = 0 \tag{16}$$

Integral gain is obtained as follows [1]

$$K_i = \frac{\omega_n}{10}\,. \tag{17}$$

Values of a chemical tanker that is not in state of equilibrium are T=-10 (s), K=-0,1(s^{-1}), $\omega_n = 0{,}05$ (rad/s), $\zeta = 0{,}8$.

$$T\ddot{\psi} + \dot{\psi} = K\delta\,, \tag{18}$$

$$s^2 T\psi(s) + s\,\psi(s) = K\delta(s)\,, \tag{19}$$

$$\psi(s)\left[Ts^2 + s\right] = K\delta(s)\,, \tag{20}$$

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{Ts^2 + s} = \frac{-0{,}1}{-10s^2 + s}\,, \tag{21}$$

$$K_p = \frac{T.\omega_n^2}{K} = \frac{-10.0{,}05^2}{-0{,}1} = 0{,}25\,, \tag{22}$$

$$K_d = \frac{2.T.\zeta\omega_n - 1}{K} = \frac{2.(-10).0{,}8.0{,}05 - 1}{-0{,}1} = 18\,, \tag{23}$$

$$K_i = \frac{\omega_n}{10}.K_p = \frac{0{,}05}{10}.0{,}25 = 0{,}00125\,. \tag{24}$$

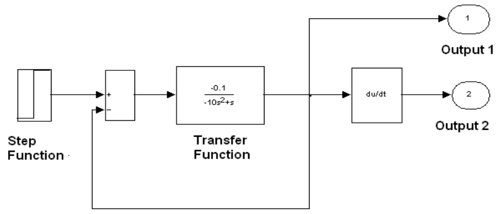

Fig. 4. Simuling model belonging to chemical tanker that is not applied controller

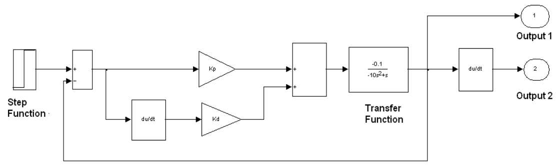

Fig. 5. Simuling model belonging to control of drifting motion of chemical tanker using PD control

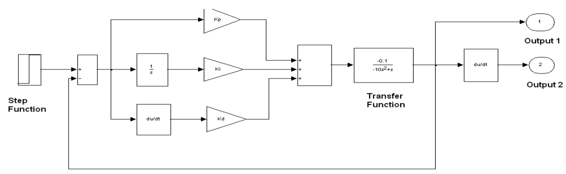

Fig. 6. Simuling model belonging to control of drifting motion of chemical tanker using PID control

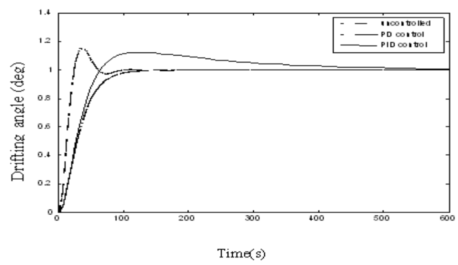

Fig. 7. Comparing of drifting angle of chemical tanker that is applied PD and PID, with not applied control

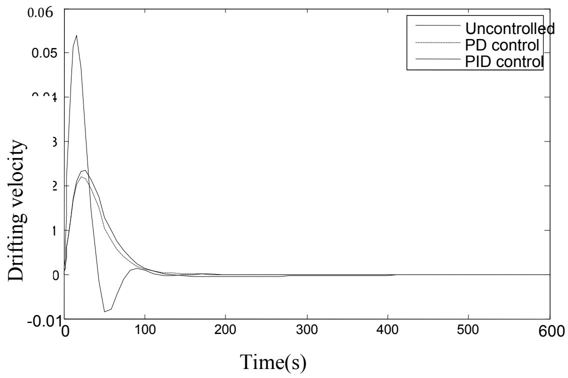

Fig. 8. Comparing of drifting velocity of chemical tanker that is applied PD and PID, with not applied control

As you see in Fig. 6, the system has become stable by making 20% overshoot in around 100 s. After all, in PD control status, although settling time seems the same as 100 s, overshoot hasn't occurred. And in PID control status, settling time is 550 s which is around 5,5 times more than all control systems and overflow has occurred as 5 %. At the same time, in PID control status, 0,02 degree of permanent settling error appears, and this is a compensating error by choosing controller parameters more eligibly. It is seen that PD control gives more proper results.

Fuzzy logic control of ship rudder system

A fuzzy logic algorithm which is a new approach in control methods has been explained in this section. Fuzzy controller error (e) and a control signal (u) according to derivative of error (ė) are generated. There are two control inputs in fuzzy autopilot using in control of drifting motion, error e =Ψd-Ψ and drifting ratio r dψ/dt are showed as rudder effect 'δ' made by controller.

The block diagram-that is formed to provide the most correct position input in control systems of drifting motion-is given in Fig. 8. Membership functions of error, derivative of error and commander have been defined one by one in controller design.

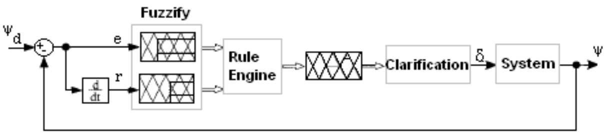

Fig. 9. Fuzzy logic block diagram of ship drifting motion

On performed fuzzy control structure, fuzzy proposal is that 'if e positive is big and $\dot{e}$ positive is big, then u positive is big'. Simulation of mathematical model of chemical tanker –that its autopilot of routa is performed with fuzzy logic approach-has been performed by using Simulink and 'Fuzzy logic' toolboxes of MATLAB packaged software.
Seven membership function is created in the process of control inputs. The calculated Membership degrees of fuzzy variables can be used in deciding process.

Table 5 shows the rules of fuzzy which are defined by a total 49 rules as each variable is expressed by seven membership functions. Error and error variation have been determined with help of this rule table.

Table 5. Rule table

de \ e	NB	NO	NK	SI	PK	PO	PB
NB	NB	NB	NB	NB	NO	NK	S
NO	NB	NB	NB	NO	NK	S	PK
NK	NB	NB	NO	NK	S	PB	PO
SI	NB	NO	NK	S	PK	PO	PB
PK	NO	NK	S	PK	PO	PB	PB
PO	NK	S	PK	PO	PB	PB	PB
PB	S	PK	PO	PB	PB	PB	PB

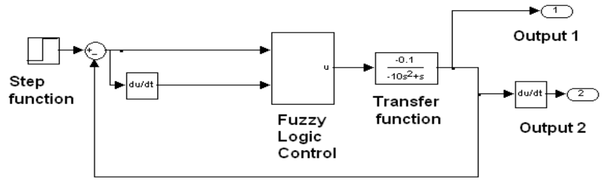

Fig. 10. Simulink model showing to control of chemical tanker's drifting motion by using fuzzy logic

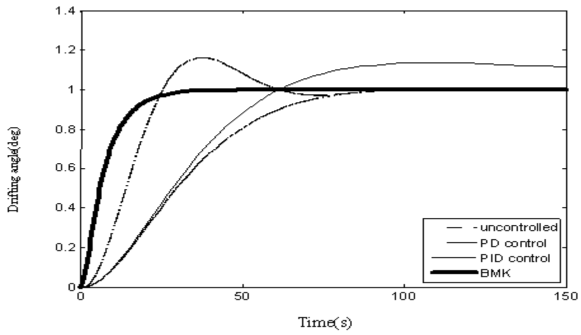

Fig. 11. Comparison of drifting angle of chemical tanker with no control and with applied PD, PID and fuzzy logic control

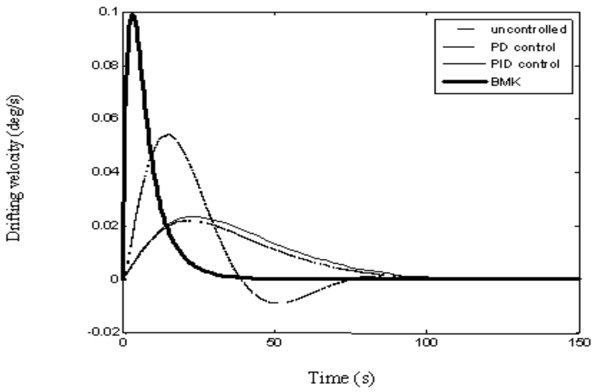

Fig. 12. Comparison of drifting velocity of chemical tanker with no control and with applied PD, PID and fuzzy logic control

Fig. 12 shows Fuzzy control drifting angle has become stable around 30 s. Error, error variation and control values have been tried to take the best result from the system in determined intervals according to the rules given in Table 5. If Table 5 is considered, it is seen from the results obtained from performed simulations that fuzzy controller system reaches reference value very rapidly. Fig. Shows that fuzzy controller bocomes stable around 25 s but the others shows the same behaoivaor at the longer time such as 100 s.

Conclusion

Manoeuvrability of ship has increased when PD and PID control methods are applied in control of chemical tanker that has hydraulic rudder system. As a result of this application, it has been observed that in non-overshoot status drifting angle settles in reference in 100 s under PD controller and it gives better results than PID controller.

Fuzzy logic control method has been developed for hydraulic in order to decrease amount of overshoot and quicken response time.

Performed simulations showed that fuzzy control is a high performance control system in a larger work zone compared to uncontrolled, PD and PID control status.

As a result, it has been observed that the best control in nonlinear systems used in ships that has hydraulic rudder system is fuzzy logic, second is PD and third is PID control system when grounding and overflow time are considered.

Acknowledgements

This research has been submitted as a master thesis by Ferhat KASAPLI and adviser Dr. Ismail TEMIZ, Pure and Applied Sciences at Marmara University.

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I. Temiz. An Investigation on the Ship Rudder with Different Control System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 9(105). – P. 28–32.

In this study, it has been searched that how control changes with different controls by discussing technical properties of a chemical tanker. Nowadays numerous control methods have been developed on this purpose. In this study, controlling of drift and roll motions of chemical tankers has been done by using proportional, integral, derivative and fuzzy logic methods. In performed simulations, second order Nomoto model has been used for drift motion that has one degree of freedom. Ill. 12, bibl. 14, tabl. 5 (in English; abstracts in English and Lithuanian).

I. Temiz. Laivo vairo su skirtinga kontrolės sistema tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 9(105). – P. 28–32.

Analizuojamos problemos susijusios su laivų valdymo sistemų pokyčių kontrole cheminių medžiagų tanklaiviuose. Šiuo metu taikoma daugybė kontrolės metodų. Diferencijavimo, integravimo ir neraiškiosios logikos metodais atlikta dreifavimo ir kryptinio judėjimo cheminių medžiagų tanklaiviuose analizė. Vieno laisvės laipsnio dreifavimo modeliavimas atliktas taikant Nomoto modelį. Il. 12, bibl. 14, lent. 5 (anglų kalba; santraukos anglų ir lietuvių k.).