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Simulation analysis of fin stabilizer on ship roll control during turning motion

Liang Lihua, Zhao Peng*, Zhang Songtao, Ji Ming, Yuan Jia

College of Automation, Harbin Engineering University, Harbin, 150001, China

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ABSTRACT

Ship turning motion is an important part of ship maneuverability and is directly related to the safety of the ship sailing at sea. Ships experience a certain amount of rolling and heeling during turning. The rolling and heeling caused by turning and waves can be large enough to affect the ability of ships to perform their missions. Fin stabilizers are currently added to ship designs for the primary purpose of producing roll-canceling moments during ordinary operation. The present work aims to investigate the effect of fin stabilizers on ship roll reduction control during turning motion. The 6-DOF mathematical model of a multipurpose navy vessel as well as the models of forces and moments caused by hydrodynamic, propeller, rudder, fins and waves are established in MATLAB. Based on the simulation analysis of ship turning motion with and without fin stabilizers, a MIGA-based improved PID controller is developed. The simulation results of ship roll control during turns using the MIGA-PID controller are compared with the results of ZN-PID and LQR controllers. Simulation results show that fin stabilizers are also effective for roll reduction control during ship turns with an appropriate controller, and the present developed MIGA-PID controller can be a practical choice.

1. Introduction

When ship sails across the sea, it always tries to keep straight sailing at a certain speed to reduce the time it takes to reach the destination and the fuel it consumes (Perez, 2005; Jin and Yao, 2013). However, when there are obstacles or other ships in its original course, the ship must change its course to avoid the incoming threats. The vast majority of ships rely upon one or more vertically oriented rudders to accomplish all maneuvers (Martin, 2003). To turn a ship, a rudder need only produce forces and moments large enough to generate rotation about the ship's vertical axis in the intended direction. However, water flowing across an angled rudder also generates roll, or rotation about the ship's longitudinal axis as the location of rudders are always below the horizontal plane the center of gravity located (Taggart, 1970; Carley and Duberley, 1972). Motivated by this phenomenon, various schemes for taking advantage of the roll moment generated by an angled rudder have been proposed and implemented, such as the rudder roll reduction (van Amerongen et al., 1990; Roberts et al., 1999; Fang and Luo, 2007) and the fin/rudder roll stabilization (Whyte, 1979; Sharif and Roberts, 2005; Jerrold and Michael, 1999; Hiroyuki and Takashi, 2004; Roberts et al., 2006).

In some situations, the ship has to conduct emergency turn to avoid incoming threats. To turn the ship in time, the rudder is usually set to a large angle and remains constant during the turn (Jin and Yao, 2013). The ship initially heels inwards, and then rolls around its longitudinal axis before attaining a steady outward heel angle as it enters the turn (Son and Nomoto, 1981). Increasing either the rudder deflection angle or ship's surge velocity tends to increase the magnitude of roll produced (Lewis, 1989). Large roll angles lead to motion sickness, cargo damage, operation interruption and even ship capsizing (Liang et al., 2017). In warships the motions may be serious enough to curtail helicopter excursions from the deck, and degrade performance of weapons systems and radars (Martin, 2003). Therefore, it is necessary to reduce the roll motion during ship turns.Fin stabilizers are the world most effective active anti-rolling device. Their anti-rolling effect at high speeds can be up to 90% in theory (Sellars and Martin, 1992). Fin stabilizers are mounted in pairs on both sides of the hull at fixed angles with respect to the transverse plane of the ship and rotated through angles of equal magnitude and opposite directions about their spanwise axis. The primary goal of designing and optimizing fin stabilizers is to obtain the maximum anti-rolling moment during ordinary operation. So far, almost all the papers related to fin stabilizers focus on the primary goal of designing, optimizing and controlling fin stabilizers to obtain the maximum anti-rolling moment to reduce ship roll motion during normal straight navigation. Few papers have been published to

* Corresponding author.
E-mail address: heu_zyy@hrbeu.edu.cn (Z. Peng).

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research the effect of fin stabilizers on ship's turning performance (Martin, 2003; Wang, 2013). The purpose of this paper is to investigate the effect of fin stabilizers on ship roll control during the turns.

Nomenclature

X	surge force	COP	centre of pressure
Y	sway force	Xc	distance between the leading edge and COP
Z	heave force	b	chord of the hydrofoil
K	roll moment	A	chord of the hydrofoil
M	pitch moment	$C_L(\alpha)$	lift coefficient
N	yaw moment	C_{D0}	minimum section drag coefficient
u	surge velocity	Λ	aspect ratio of the hydrofoil
v	sway velocity	LCG	yaw arm of the rudder
w	heavy velocity	r_r	roll arm of the rudder
p	roll velocity	δ	rudder angle of attack
q	pitch velocity	ε	straightening effect coefficient
r	yaw velocity	β	drift angle at CG
φ, ϕ	roll angle	U_S	ship speed during steady turning period
θ	pitch angle	FCG	yaw arm of the fin
ψ	yaw angle	NCG	pitch arm of the fin
m	ship mass	r_f	roll arm of the fin
CG	centre of gravity	β_{fin}	tilt angle of the fin
x_G	x-coordinate of CG	α_f	fin angle of attack
z_G	z-coordinate of CG	ζ_n	wave height of the nth regular wave
I_x	moment of inertia about x axis	$S_\xi(\omega)$	wave-height spectrum
I_y	moment of inertia about y axis	$\Delta\omega_n$	frequency interval
I_z	moment of inertia about z axis	$h_{1/3}$	significant wave height
ρ	fluid density	NN	number of regular wave components
g	gravitational acceleration	ω_e	encounter frequency
$\bigtriangledown$	ship displacement	ω_n	frequency of the nth regular wave
$GZ(\varphi)$	roll righting arm	ε_n	random phase of the nth regular wave
F	resultant hydrodynamic force	t	time
L	lift force generated on the hydrofoil	χ	encounter angle
D	drag force generated on the hydrofoil	L_s	wavelength of the nth regular wave
T	tangential force generated on the hydrofoil	k_n	wave number of the nth wave number
N	normal force generated on the hydrofoil	VCG	vertical distance between CG and baseline
α	angle of attack of the hydrofoil	U_0	initial sailing speed before ship turning
U	inflow velocity (≈ ship speed)	R_0	steady turning radius
a	distance between the leading edge and hydrofoil shaft	d	ship average draft
		φ_0	steady outward heel angle
		h	transverse metacentric height

To achieve the optimal roll reduction, fin stabilizers need to incorporate the automatic controller. Therefore, a suitable controller is important to achieve satisfactory anti-rolling effect. So far, PD control (Fang et al., 2012), PID control (Crossland, 2003; Fang et al., 2010), LQR control (Lee et al., 2011; Yuan, 2014), adaptive control (Nejim, 2000; Carletti et al., 2009; Li et al., 2016), fuzzy control (Roberts et al., 1999; Cao and Lee, 2003), sliding mode control (Mcgookin et al., 2000; Fang and Luo, 2007) and robust model predictive control (Ghaemi et al., 2009) have been developed and applied to the controller design of fin stabilizers. Among them, the PID controller may be the most extensively applied one in practical application for its high reliability and strong robustness. In this paper, an improved PID controller is developed to control the fin stabilizers to reduce ship roll motion during turns. However, the control parameters of PID controller are usually determined based on the experience of operators, trial-and-error method or experiments, which might not be the optimal (Fang et al., 2010). Genetic Algorithm (GA) recently has received some attention for these problems and can be used to promote the efficiency of the controller (Fang and Luo, 2007; Gupta et al., 2018). Genetic Algorithm reflects many advantages, such as simple currency, strong robustness and suitable for parallel processing (Goldberg, 1989; Hu et al., 2014). But there are still some practical issues, such as poor local search, premature convergence, slow convergence rate (Chen and Lin, 2004). Thus, it is necessary to make an improvement and the multi-island genetic algorithm (MIGA) is adopted in this paper to optimize the control parameters for the improved PID controller.

The structure of the paper is as follows. Section 2 establishes the mathematical models of 6-DOF ship motion and the forces and moments of hydrodynamic, propeller, rudder, fin stabilizer and disturbance. Section 3 simulates and analyzes ship's turning motion in calm water with and without fin stabilizers and verifies the established mathematical model. Section 4 gives the controller design and MIGA-based control parameter optimization. Section 5 is the results and discussion. Finally, the conclusion is given.

2. Ship modeling

A ship in a seaway moves in six degrees of freedom. As shown in Fig. 1, two type of reference frames, the inertial frames and body-fixed frames, are used to describe its motion.

In the modeling of ship motion, the ship is usually considered as a rigid body and the ship motion model can be obtained according to Newton law (Abkowitz, 1964). The 6-DOF ship motions are mutually coupled with different coupling strength. The mathematical model of ship motion can be simplified according to the coupling strength and specific research purpose. This paper aims to investigate the effect of fin stabilizers on ship roll reduction control during ship turning. Therefore, the mathematical model of ship motion in surge, sway, roll and yaw is needed. The pitch and heave are also considered as the effect of pitch attitude in damping and the high coupling between pitch and heave. Therefore, the 6-DOF mathematical model of ship motion is established as follows (Perez, 2005).