Ocean Engineering 148 (2018) 602–611

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Design of a safety operational envelope protection system for a submarine

Jong-Yong Park [a], Nakwan Kim [b,*]

[a] Institute of Engineering Research, Seoul National University, Seoul, South Korea
[b] Department of Naval Architecture and Ocean Engineering, Research Institute of Marine Systems Engineering, Seoul National University, Seoul, South Korea

ARTICLE INFO

Index Terms:
Command limiting
Dynamic trim algorithm
Envelope protection system
Neural network
Safety operational envelope
Submarine

ABSTRACT

A safety operational envelope (SOE) is an area that guarantees the safety of a submarine from accidents, such as jamming and flooding. In this study, a submarine envelope protection system (EPS) was designed to prevent submarine excursion from the SOE. Modeling of the hull force, propeller force, and main ballast tank blowing was performed. The SOE was established based on a crash stop and emergency rising maneuver simulation. In the estimation model, a linear compensator and neural network are employed to estimate the submarine dynamics. The command limit is calculated using the estimation model and the dynamic trim algorithm, and it is restricted by the limit avoidance. The EPS was applied to a submarine maneuvering simulation program and its performance was verified by a depth change simulation. The designed EPS prevents the submarine from exceeding the limit boundary and the control system can thereby enhance the operational stability.

1. Introduction

Since the submarine was first developed, approximately 170 of these vessels have sunk as a consequence of an accident, such as a fire, explosion, malfunction, or collision. Submarine accidents can cause casualties as well as marine pollution. The safety operational envelope (SOE)—also known as the maneuvering limitation diagram (MLD)—was established to reduce the occurrence of these accidents. SOE refers to the area obtained by defining the excursion depth during accidents, such as jamming and flooding, for various speed conditions. The helmsman is currently responsible for SOE protection. The helmsman is trained on numerous types of equipment and guidelines for ensuring safety by preventing transgression of SOE limits. The envelope protection system (EPS) is a control system that guarantees that a moving body operates within its own SOE. Because it can reduce operational accidents and enable an effective mission by utilizing a region boundary, EPS application can improve the safety and maneuvering performance of submarines (Sahani, 2005). Research topics relating to EPS for a submarine include maneuvering motion modeling and motion control. Representative areas for each subject are outlined in the sub-sections below.

1.1. Maneuver motion modeling

Simulation of submarine maneuvering is generally based on Gertler equations of motion (Gertler and Hagen, 1967). The model was revised by Feldman in 1979 (Feldman, 1979) to provide enhanced nonlinear modeling for the cross-flow drag and sail vortex. Many studies have aimed to obtain the coefficients of the maneuvering model using captive model tests. The planar motion mechanism (PMM) and rotating arm (RA) tests have been generally used to determine the coefficients in the models (Feldman, 1987, 1995; Roddy et al., 1995). Researchers at the Defense Science and Technology Organization (DSTO) experimentally evaluated a generic submarine model in a wind tunnel (Quick et al., 2012, 2014). The standard submarine model was developed for a series of systematic hydrodynamic experiments jointly funded by Defense R&D Canada and the Royal Netherlands Navy, and it has been statically tested at different facilities (Mackay, 2003). Watt (2007) and Bettle et al. (2009) performed emergency rising maneuver simulations based on experimental data and computational fluid dynamics (CFD), respectively.

1.2. Motion control

Most studies on submarine motion control have focused on depth-keeping in waves. Research activities on depth control for a submarine that navigates near the free surface are mainly performed using the respective proportional-integral-derivative (PID) controller, linear-quadratic regulator (LQR), gain scheduling, and adaptive control. Dumlu and Istefanopulos (1995) designed a depth controller based on gain scheduling for operation in various sea conditions. A mathematical model was proposed for calculating the wave forces on the submarine,

* Corresponding author. Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, 08826, South Korea.
E-mail address: nwkim@snu.ac.kr (N. Kim).

https://doi.org/10.1016/j.oceaneng.2017.11.016
Received 18 January 2017; Received in revised form 20 September 2017; Accepted 8 November 2017

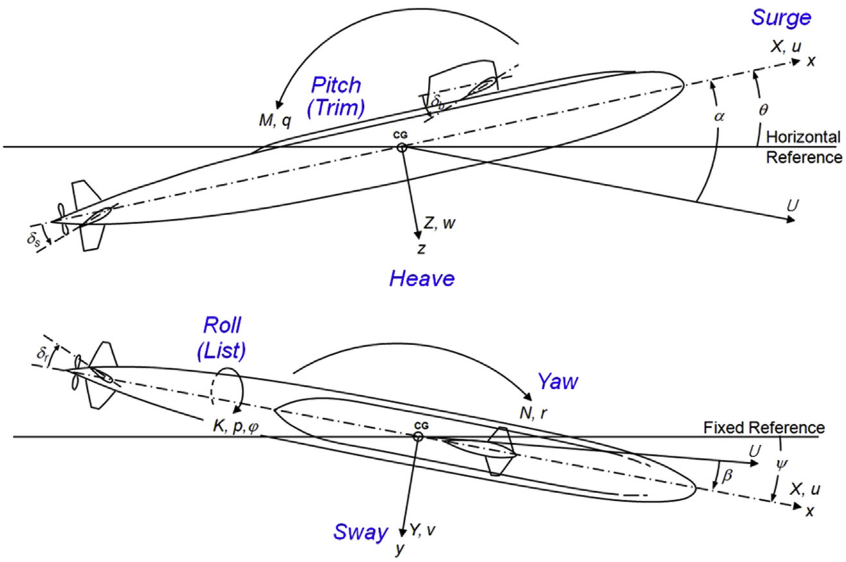

Fig. 1. Coordinate system (Park et al., 2017).

and a PID control method was used to confirm the possibility of control through simulations (Choi, 2006). Kim et al. (2009) analyzed the limitations of PID control and designed a depth controller using the LQR control method. Lee and Singh (2014) used the L1 control method to design a depth controller. They conducted depth-keeping simulations under random disturbances to verify the controller robustness.

1.3. Envelope protection system

EPS studies have been conducted since the 1990s in the aeronautical field. Some algorithms are available for EPS, including the peak response estimation and the dynamic trim algorithm. The peak response estimation algorithm is suitable for dynamics with overshoot. The algorithm is used to estimate the peak value of the limit parameter induced by control input. It is used to avoid the limit of the rotor hub moment and flapping of a helicopter (Sahani, 2005; Horn et al., 2001). The dynamic trim algorithm was proposed by Horn et al. (1998) and is widely used for EPS. The algorithm can predict the control input that forces the limit parameter to exceed the restricted limit using the quasi-steady-state condition. The algorithm was modified by Horn et al. (2002), Yavrucuk (2003), and Unnikrishnan et al. (2011) into an online training method using a neural network (NN) that is adaptable to various operational conditions. Applications of the above algorithms to various aircraft—such as fixed wing, rotary wing, and autonomous unmanned aerial vehicles—have been undertaken in aeronautics (Yavrucuk et al., 2009; Yavrucuk and Prasad, 2012; Shin et al., 2011; Gursoy and Yavrucuk, 2014; Tekles et al., 2016).

Studies on submarine operational stability mainly deal with the course-keeping ability, instability of roll motion, or depth-keeping in waves based on the experimental data and CFD. Research on the carefree maneuvering system for the submarine using EPS is in nascent stages. The aim of this study is to design an EPS that ensures the speed, depth, and pitch angle of the submarine within a predefined SOE. A six-degrees-of-freedom equation of motion, deduction of hydrodynamic coefficients from experimental results, and SOE calculation of the submarine are required to design the EPS. The maneuvering motion equation is established based on Gertler and Hagen's research (Gertler and Hagen, 1967). Main ballast tank (MBT) blowing modeling and propeller force modeling are conducted to simulate the accident and recovery process. The SOE of the submarine is determined by the emergency rising maneuver and crash-stop simulation results. The linear approximation model, linear compensator, and NN are adopted for closed-loop dynamics estimation of limit parameters, such as speed, depth, and pitch angle. The dynamic trim algorithm and fixed-point iteration method are adopted for limit detection. The limit avoidance scheme is based on a command-limiting architecture that is designed to protect excursions in the limit parameters. Depth-changing simulations near the SOE boundary were conducted to confirm the EPS performance.

The remainder of this paper is structured as follows. Equations of motion and the external force modeling are provided in Section 2. In Section 3, the submarine SOE is calculated based on the maneuvering simulation. The EPS designs for speed, depth, and pitch angle are described in Section 4, and simulation results with and without the EPS are presented in Section 5. Finally, conclusions are provided in Section 6.

2. Equations of motion

In this section, the submarine equations of motion are described. The coordinate system consists of the space-fixed coordinate $O-x_s y_s z_s$ and body-fixed coordinate $o-xyz$. The coordinate system used in this study is shown in Fig. 1.

$$
\begin{aligned}
m\left[\dot{u}-vr+wq-x_G\left(q^2+r^2\right)+y_G(pq-\dot{r})+z_G(pr+\dot{q})\right] &= X \\
m\left[\dot{v}-wp+ur-y_G\left(r^2+p^2\right)+z_G(qr-\dot{p})+x_G(qp+\dot{r})\right] &= Y \\
m\left[\dot{w}-uq+vp-z_G\left(p^2+q^2\right)+x_G(rp-\dot{q})+y_G(rq+\dot{p})\right] &= Z \\
I_x\dot{p}+\left(I_z-I_y\right)qr-I_{xz}(\dot{r}+pq)+I_{yz}\left(r^2-q^2\right)+I_{xy}(pr-\dot{q})+m[y_G(\dot{w}-uq+vp)-z_G(\dot{v}-wp+ur)] &= K \\
I_y\dot{q}+\left(I_x-I_z\right)rp-I_{yx}(\dot{p}+qr)+I_{zx}\left(p^2-r^2\right)+I_{yz}(qp-\dot{r})+m[z_G(\dot{u}-vr+wq)-x_G(\dot{w}-uq+vp)] &= M \\
I_z\dot{r}+\left(I_y-I_x\right)pq-I_{zy}(\dot{q}+rp)+I_{xy}\left(q^2-p^2\right)+I_{zx}(rq-\dot{p})+m[x_G(\dot{v}-wp+ur)-y_G(\dot{u}-vr+wq)] &= N
\end{aligned}
\tag{1}
$$

The origin of the body-fixed coordinate is located at the mid-ship on the center line. The six-degrees-of-freedom equations of motion can be