Ocean Engineering 35 (2008) 1747–1758

Contents lists available at ScienceDirect

Ocean Engineering

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

Efficient multivariable submarine depth-control system design

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ARTICLE INFO

Article history:
Received 18 January 2008
Accepted 29 August 2008
Available online 27 September 2008

Keywords:
Multivariable control systems
Frequency-domain design
Individual channel analysis and design
Submarine
Depth control

ABSTRACT

An efficient solution for the multivariable submarine control design at low-depth conditions under the influence of wave disturbances is presented. The analysis and control design process is carried out under the framework of individual channel analysis and design (ICAD), which is based on the multivariable structure function (MSF). Classical frequency-domain control techniques based on Bode and Nyquist plots are used. Robustness is stated in terms of gain and phase margins. The closed-loop system includes low-order diagonal controllers facilitating its implementation, assessment, and tuning. ICAD discloses new physical insights of the submarine dynamical behaviour. Previous designs based on diagonal controllers consider the input–output channels defined by pairing the bow hydroplane angle with the depth and the stern hydroplane angle with the pitch angle. The alternative input–output pairing leads to unstable closed-loop systems. This phenomenon is associated with hydroplane reverse control. Here it is shown that MSF-based diagonal controllers can be applied effectively for both sets of channel configurations. Emphasis is placed on satisfying design specifications aiming at maintaining the depth low. The solution presented is more feasible and clearer to apply in practice than those so far reported in the literature.

1. Introduction

The analysis and design of low-depth-keeping multivariable autopilots for the well-validated 80-m British submarine model are presented.

Submarines operating at deep submergence can be considered to be in a wave-free environment. This is due to the fact that the effect of wave disturbances decreases exponentially with depth. In general, the design of high submergence submarine depth-keeping controllers is a straightforward task. On the other hand, at shallow submergence, under rough sea conditions and low speed, the design of effective depth-keeping autopilots requires further analysis and full comprehension of the effects of sea-wave disturbances on the boat. Shallow submergence operations rely on keeping the submarine at constant depth relative to a calm surface with zero mean pitch angle (Marshfield, 1991; Marshfield et al., 1992; Williams and Marshfield, 1990, 1991a; Ferranti International, 1993). Low depth-keeping controllers must be designed considering the characteristics of the wave disturbances whose effects are twofold (Marshfield et al., 1992; Ferranti International, 1993). In the first place, there are regular wave forces and moments associated with short and long wave components. They are referred to as the first-order wave effects. The forces and moments due to short wave components cancel along the hull, whereas the submarine contours the longer period waves. For control design purposes, first-order wave disturbances must be neglected as the hydroplanes cannot produce enough forces and moments to counteract the longer wave effects and the frequency of the shorter wave components are beyond the hydroplanes effective bandwidth. The second effect is associated with the irregular components of the waves which produce an upward net force. It is the average component of this suction force that needs to be counteracted by the depth-keeping controller. At the same time, the controller must ignore the first-order disturbance components in order to avoid saturation and nugatory activity of actuators. High activity of the actuators may reduce the stealth characteristics of the submarine.

Earlier depth-control autopilots were found in German submarines at the end of the II World War (Burges, 1975). It is known that French submarines included improved versions of the German designs after the war (Bovis, 1988). The works of Arentzen and Mandel (1960) and Nonweiler (1961) gave rise to the development of depth-keeping controllers in the UK. These earlier

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0029-8018/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2008.08.018

Nomenclature

w	heave velocity
q	the pitch rate
θ	pitch angle
z	submarine depth
δ_B	bow hydroplane angle
δ_S	stern hydroplane angle
u_0	boat speed
$y = [z, \theta]^T$	output vector
$u = [\delta_B, \delta_S]^T$	input vector
$G(s)$	transfer matrix
$g_{ij}(s)$	scalar transfer function elements of $G(s)$
$K(s)$	multivariable controller
$k_{ii}(s)$	ith diagonal element of $K(s)$
$e_i(s)$	ith error signal
$r_i(s)$	ith plant reference
$y_i(s)$	ith output
$u_i(s)$	ith input
$C_i(s)$	ith individual channel
$\gamma(s)$	multivariable structure function
$h_i(s)$	individual subsystem transfer function
$G_{cl}(s)$	closed-loop matrix transfer function
RHPP	right hand plane pole
RHPZ	right hand plane zero
P	number of RHPPs of $\gamma(s)h_i(s)$
N	number of clockwise encirclements of the Nyquist plot of $\gamma(s)h_i(s)$ to the point $(1, 0)$ of the complex plane
Q	number of RHP eigenvalues of the state-space representation
$\gamma_a(s)$	multivariable structure function when pairing ith input to ith output
$\gamma_b(s)$	multivariable structure function when pairing ith input to jth output

controllers are typical single-input single-output (SISO) PD-type designs in which bow and stern hydroplanes are geared together. Although the details with regard to the performance of these earlier autopilots is not public, it is known that the 'split plane mode', that is, the independent use of bow and stern hydroplanes improves the performance of depth-keeping controllers (Braugnier, 1966). This fact motivated the research on multivariable depth-keeping control systems. In the UK such work was carried out as a joint venture between the University of Cambridge and the Royal Admiralty (Haslar, UK) in which optimal control with Kalman filter methods were applied. Some of the results obtained are reported in Booth (1983), Daniel (1981), Richards and Stoten (1981), Daniel and Richards (1982, 1983). Similar works are reported by Gueler (1989), Zhao and Yan (1989) and Lively (1983). By considering the shallow-depth-keeping of submarines as a multivariable control problem, some improvements are achieved. Sea trial results are not of public domain; nevertheless, it is claimed in Lively (1983) that under sea disturbances, the performance is still poor with such control schemes. Kalman filters were also considered in order to cope with sea disturbances. However, in Daniel and Richards (1982), it is reported that the results obtained were less successful than those expected.

Robust control theory opened up new options for developing better designs. This approach was used by the British Defence Research Agency (Marshfield, 1991; Williams and Marshfield, 1990, 1991a, 1991b). These reports show better performance than earlier designs. Nevertheless, a clear and appropriate manner for selecting a good set of weighting functions was and is still lacking. In order to determine a clear and systematic manner for designing depth-keeping controllers, further work was developed by the British Defence Research Agency and the Industrial Control Centre of Strathclyde University. Some of the results obtained during that research programme are reported in Licega-Castro and van der Molen (1995a, b). The main contribution of Liceaga-Castro and van der Molen (1995a) is the definition of a set of control design specifications. These were tailored bearing in mind the wave disturbances effects on the boat and their influence on the activity of the control system. That is, the control specifications were defined in such a way that the controller ignores the regular wave disturbances forces but reacts effectively to the irregular wave effects. The controller presented is obtained considering measurement of the pitch angle, heave velocity, and depth. On the other hand, the work presented in Liceaga-Castro and van der Molen (1995b) defines a systematic and clear design procedure using robust techniques considering the design specifications defined in Liceaga-Castro and van der Molen (1995a). Nevertheless, the selection of linear wave models for design purposes is not an easy task.

The analysis of the dynamical structure of the submarine model used in Liceaga-Castro and van der Molen (1995a) and Liceaga-Castro and van der Molen (1995b) is presented through the ICAD framework in Liceaga-Castro and Liceaga-Castro (1998). In this work, only the pitch angle and depth measurement are considered available for feedback. The main result presented in Liceaga-Castro and Liceaga-Castro (1998) is that the fundamental aspects for designing effective diagonal low-depth-keeping submarine controllers are established. Such specifications are defined in terms of bandwidth, stability margins and roll-off slope.

A key conclusion derived from the nonlinear simulations results reported in Liceaga-Castro and van der Molen (1995a) and Liceaga-Castro and van der Molen (1995b) is that, regardless of the method used to design the controller, the success of the design depends on satisfying the design specifications defined in Liceaga-Castro and van der Molen (1995a).

The aim of this paper is to formalise the ICAD design procedure of low-depth-keeping submarine controllers and to complement the results presented in Licega-Castro and van der Molen (1995a, b) and Liceaga-Castro and Liceaga-Castro (1998). In addition, concluding aspects with regard to the comparison of the nature of the controllers obtained under the ICAD framework and the so-called robust methods are stated. For instance, the ICAD approach allows to satisfy design specifications (robustness and performance) and avoids unnecessary sophisticated controllers in a clear and transparent constructive manner. Unlike H^∞-related methods (Liceaga-Castro and van der Molen, 1995b), in the ICAD-based approach, the characteristics of the submarine dynamical structure are not hidden. Furthermore, new physical characteristics are revealed. Namely, it is shown that by analysing the MSF, it is possible to design multivariable diagonal stabilising controllers for every input–output channel configuration. A diagonal control in which the input–output channels are defined by pairing stern hydroplanes with depth and bow hydroplanes with pitch results in an unstable closed-loop system, which gives rise to the *reverse hydroplane control effect* (Spencer, 1980).

A crucial aspect of ICAD is that robustness for multivariable systems is expressed in terms of gain and phase margins, which are well-proven robustness measurements in engineering practice. Thus, the lack of robustness pointed out in Keel and Bhattacharyya (1997) and Nesline and Zarchan (1982), associated with modern techniques, is avoided.