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Optimal controllers for rudder roll damping with an autopilot in the loop ⋆

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Abstract:
In this paper we propose a new approach to the design of a rudder roll stabilization system, integrated with a predesigned heading controller (autopilot). Whereas a number of methods for the roll oscillation damping have been proposed in the literature, this problem still remains challenging. In this paper we consider a linear-quadratic optimization problem, where the cost functional penalizes the roll angle, the heading deviation and the control effort (rudder angle). Approximating the wave disturbance by a polyharmonic signal with a known spectrum, we design a controller, which optimizes this quadratic performance index, providing thus a "trade-off" between the maintenance of the desired heading, roll damping and the steering system utilization. The practical applicability of our algorithms is illustrated by numerical simulations.

Keywords: Rudder roll stabilization, oscillation damping, universal controller, ship autopilot

1. INTRODUCTION

Roll damping systems are used to reduce the roll motion of a marine vessel, preventing motion sickness of the crew and passengers and potential cargo damage. The ideas of roll stabilization date back to the late 1800s, see e.g. the historical surveys in (Perez, 2006; Perez and Blanke, 2012).

In this paper we consider the problem of *rudder* roll stabilization, which has been studied in the literature since 1970s (Cowley and Lambert, 1972). In this problem, the same rudder is used for both heading control and roll reduction; consequently, the vessel appears to be an *underactuated* system. Designing a controller, one has to provide a "trade-off" between the accuracy of the heading maintenance and the roll damping efficiency in the face of the rudder angle and rate of turn limitations, imposed by the steering machine.

A number of approaches to the rudder roll stabilization have been proposed in the literature. Among them are the gain scheduling adaptive control (van Amerongen et al., 1986), frequency-domain techniques (Horowitz and Sidi, 1978; Hearns and Blanke, 1998) and the sliding mode control (Lauvdal and Fossen, 1995). A number of convenient design procedures are based on optimal control methods such as the LQG-optimization (van Amerongen et al., 1990; van der Klugt, 1987; Anderson and Moore, 1990) and the H_∞ optimal control (Stoustrup et al., 1994). A disadvantage of these optimization-based methods is the explicit use of wave disturbance models. Typically, the ocean wave is represented by a "colored noise", whose spectral density is explicitly known.

In this paper we offer a novel optimization-based approach to rudder roll stabilization, based on the idea of V.A. Yakubovich's *optimal universal controller* (OUC) (Yakubovich, 1995; Proskurnikov, 2015; Lindquist and Yakubovich, 1997; Yakubovich et al., 2011; Proskurnikov and Yakubovich, 2012). An OUC solves the problem of linear-quadratic optimization in presence of *uncertain* external disturbances, approximated by polyharmonic signals with known spectrum yet unknown amplitudes. The term "universal" emphasizes that the controller delivers the optimal process for an *arbitrary* signal from this class. Our approach thus differs from classical methods in robust control (e.g. $\mathcal{H}_\infty$- and L_1-optimization theories) and stochastic control, optimizing the performance index either for the "worst-case" signal or "on average". Unlike the classical LQR problem, the performance index stands not for the "energy" (L_2-norm) of the process, but for its "average power", which enables one to deal with non-decaying solutions. The OUC, minimizing such a cost-functional, is typically non-unique and can be found without solving Lur'e-Riccati equations (Anderson and Moore, 1990). Using the Yakubovich OUC, one does not need the exact model of the wave motion, but has to estimate its "dominating" frequencies.

The paper is organized as follows. In Section 2 the vessel model and the disturbances are introduced. In Section 3 the main results are presented, concerned with the roll damping controller design. These results are illustrated by simulations in Section 4.

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2. MATHEMATICAL MODELS

2.1 Notations

Throughout the paper $\mathbb{R}$ and $\mathbb{C}$ denote, respectively, the sets of real and complex numbers. The imaginary unit is denoted by $\imath \triangleq \sqrt{-1}$. For a complex number $z \in \mathbb{C}$, we use $Re(z)$ and $Im(z)$ to denote, respectively, its real and imaginary parts. The symbol * stands for the Hermitian complex-conjugate transpose.

2.2 Ship dynamics

The dynamics of marine vessels can be described using a general nonlinear six degree-of-freedom model. Although this model has a high accuracy, its complexity makes it very difficult to be used to analyze and design control laws. A widely used paradigm in roll stabilization control is to use linear models with the assumption that the system's states are within small deviation from the steady-state values. In this paper the model derived from data obtained from a series of full-scale modeling trials by van der Klugt (1987) will be used. For simplicity, the rudder angle $\delta(t)$ is considered as the only input. The surge velocity is assumed to be constant. When the rudder is turned, a lift force appears on the rudder. This force produces a yaw moment, rolling motion and undesirable sway motion. To describe these motions, the following transfer functions are used:

$$\begin{aligned} W_{sway}(s) &= \frac{K_{dv}}{(\tau_v s + 1)}, \\ W_{yaw}(s) &= \frac{1}{(\tau_r s + 1)s}, \qquad (1) \\ W_{roll}(s) &= \frac{\omega_n^2}{s^2 + 2\zeta_n \omega_n s + \omega_n^2}, \end{aligned}$$

where $K_{dv}, \tau_v, \tau_r, \zeta_n, \omega_n$ are the fixed parameters.

Taking into account the rudder forces and the disturbances, the vessel's model is as follows

$$\begin{aligned} \psi(t) &= W_{\psi\delta}\left(\frac{d}{dt}\right)\delta(t) + W_{yaw}\left(\frac{d}{dt}\right)d_\psi(t), \\ \varphi(t) &= W_{\varphi\delta}\left(\frac{d}{dt}\right)\delta(t) + W_{roll}\left(\frac{d}{dt}\right)d_\varphi(t), \qquad (2) \\ W_{\psi\delta}(s) &\triangleq W_{yaw}(s)(K_{dr} + K_{vr}W_{sway}(s)), \\ W_{\varphi\delta}(s) &\triangleq W_{roll}(s)(K_{dp} + K_{vp}W_{sway}(s)), \end{aligned}$$

where $\psi(t)$, $\varphi(t)$, $\delta(t)$ stand, respectively, for the heading (yaw), roll and rudder angles (see Fig. 1). The signals $d_\psi(t)$ and $d_\varphi(t)$ are disturbances, describing the influence of the environment on the yaw moment and the roll moment respectively, $K_{dr}, K_{vr}, K_{dp}, K_{vp}$ are the fixed parameters. The full stricture of the model is shown in Fig. 2.

2.3 The disturbance models

The disturbances acting on a marine craft are due to the wind, the waves and the current. The fast oscillations in the vessel's roll angle $\varphi(t)$ and its heading $\psi(t)$ are mainly caused by the waves, whereas the current and the wind are changing much slower and their effect is usually modeled as a constant roll angle and stationary heading deviation. To simplify the model, we consider henceforth only the influence of wave disturbances.

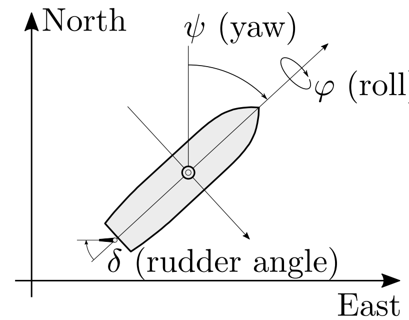

Fig. 1. Motion coordinate system

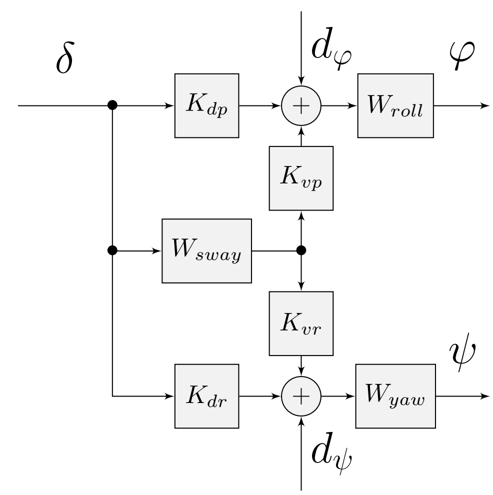

Fig. 2. The structure of the vessel's model

The waves are typically represented by their frequency spectrum. A commonly used model for the wave motion is a colored noise (Fossen, 1994; Perez, 2006), which can be obtained by feeding the white noise to a low-pass shaping filter. A good approximation to the real wave spectrum is given by the filter with the rational transfer function

$$H(s) = \frac{K_w s}{s^2 + 2\zeta_0 \omega_0 s + \omega_0^2}. \qquad (3)$$

Here K_w is a coefficient, standing for the wave strength, ζ_0 is a damping ratio and ω_0 is the encounter frequency.

An alternative approximation of the wave motion is a sum of harmonic (sinusoidal) signals. The approach, used in this paper, provides the optimal (in the sense of a quadratic cost function) roll damping for polyharmonic signals with a known spectrum, but *uncertain* amplitudes and phase shifts. Although the actual wave signal is not polyharmonic, it typically has several dominating frequencies, whereas the energy of the remaining spectrum is small. The optimal controller, designed for the dominating frequencies, provides an approximate (suboptimal) solution to the optimization problem.