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Roll Damping Using Voith Schneider Propeller: a Repetitive Control Approach [*]

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Abstract: Voith Schneider propellers are potential propulsion systems for dynamic positioning in offshore applications because of their fast and accurate thrust generation. An overlaid roll damping control by the same propulsion system is possible to reduce the influence of external disturbances. The paper at hand presents simulation results of roll damping control using a repetitive control approach. Repetitive control is a highly effective control technique for the compensation of periodic disturbances, or for exact tracking of periodic reference signals. Simulation results of repetitive control in roll damping will be compared with those from a classical approach. The simulation models as well as the disturbance signals are based on theoretical considerations as well as on verifying experiments in a towing tank. The robustness of the method has been investigated according to deviations from a purely periodic excitation as well as to the influence of propulsion saturation.

Keywords: Marine systems, Periodic waves, Compensating feedback, Disturbance rejection, Robust control, LQR control method, Saturation, Computer simulation

1. INTRODUCTION

A critical requirement in offshore service is the ability of marine vessels to hold the position with certain accuracy despite external disturbances. Voith Schneider propellers (VSP) are an excellent propulsion system due to their dynamic positioning (DP) objective. Because of its construction, VSP can variegate thrust and direction of thrust in very short time. It makes maneuvering fast and accurate compared to propeller-based propulsion, Palm and Jürgens (2009).

Most solutions for roll reduction are referred to cruising vessels. The reduction supports the safety of crew and cargo and is achieved by additional aggregates like fins, bilge keels, tanks, and special rudders. Rudder stabilization is relatively inexpensive, but is ineffectual for low speed or positioning of ships Fossen (2011). The publication Perez (2006) reduces the roll motion in cruise by various constellations of rudders and fins. Sørensen and Strand (2000) describe a combined control using static allocation.

Due to distinct frequency regions of wave disturbances and position adjustment, the highly dynamic VSP system is able to achieve DP and roll damping at the same time by the propulsion unit. The roll damping is realized as overlaid control on the DP output. There are few examples for combined DP and roll damping control. At first roll damping with VSP has been investigated in Palm and Jürgens (2009). In Brandner (2014) and Jürgens et al. (2012) the authors described optimal control and allocation for VSP and compared the results to steerable, propeller-based propulsions.

The investigations presented in this paper are affiliated to Koschorrek et al. (2015). The DP system using VSP propulsion consists of PID control with dynamic allocation in 3 degrees of freedom (3DOF). The basic roll damping was realized by PD controller.

A repetitive loop is implemented in addition to a basic controller. The results will be discussed by basic roll stabilization with and without saturation as well as this classic roll damping supplemented by a repetitive component. Conditions should be surveyed, under which repetitive control is a beneficial tool in roll reduction, when only one propulsion system is available.

2. PRELIMINARIES

2.1 Repetitive control

The basic idea of repetitive control goes back to the internal model principle, orginated by Francis and Wonham (1976). It means that deviations due to an external signal can be perfectly removed by the control loop, if an exact model of the external signal is included as plug-in in the control loop. A feedback with delay T can be used as internal model for an arbitrary signal of period T. It can generate the first harmonic with frequency $\omega = 2\pi/T$ and all higher harmonics. Therefore, the most characterizing module of the internal model (IM) of periodic signals is the time delay. The structure of the repetitive control plug-in as part of the control loop is shown in Fig. 1.

Repetitive control was applied successfully for systems with periodic external excitation, at first in disk drive

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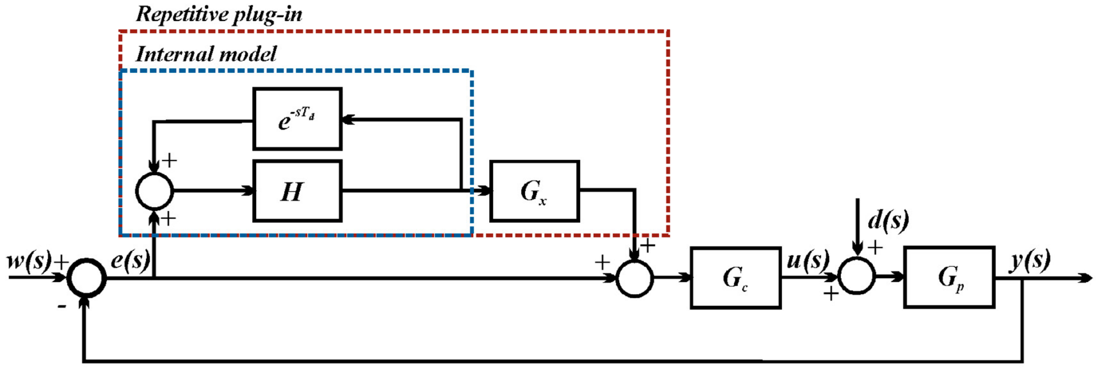

Fig. 1. Basic structure of repetitive controller implementation in closed-loop system according to Cuiyan et al. (2004)

systems (Chew and Tomizuka (1989)) characterized by the periodic reference signal. The periodic excitation also can come from disturbances, like in motor-gear transmission systems (Sangeetha and Jacob (2008))

Various modifications to the basic structure have been developed to meet different requirements. For instance, nearly periodic excitation with a dominant period T_d can be assumed for the external signal. Also different weighted time delays can be included for better adaption of the exciting signal. A low-pass filter $H(p)$ can be added to improve the robustness against high frequencies in the control signal due to the infinite gain in the IM harmonic frequencies. In the desired bandwidth, $H(p)$ has a gain close to 1 but in higher frequencies a strong attenuation. $G_x(s)$ is implemented for further stabilization of the closed loop. It is the inverse of closed loop function $G_0(s)$ without the plug-in in the case of a minimum phase system. Additionally, a factor k_r is included in $G_x(s)$ as a trade-off between control robustness and performance. $G_c(s)$ is the classic nominal controller to stabilize the plant $G_p(s)$ Ramos et al. (2013).

In roll stabilization, waves of a certain spectrum act on the roll motion process as disturbance. Each vessel is characterized by a typical roll frequency depending on construction data. This frequency provides the dominant period for applying repetitive control in roll damping.

2.2 Modeling of roll motion

In order to model the roll motion, hydrodynamics, hydrostatic and external forces and moments have to be considered. Perez (2006) has derived complete roll motion equations including couplings of roll and sway/yaw. Although these degrees are tightly coupled, their interaction has been neglected for simplicity and control design in one degree of freedom. The relation between the roll angle ϕ and an external roll moment K_{ext} can be modelled by

$$\begin{aligned} K_{ext} &= K_c + K_u \\ &= (K_{\dot{p}} - J_x)\dot{p} \quad + (K_p + K_{p|p|}|p| + K_{|u|p}|U|)p \\ &\quad + (K_{\phi uu}U^2 + K_{\phi\phi\phi}\phi^2 + \Delta g\rho\overline{GM}_T)\sin\phi \end{aligned} \tag{1}$$

where K_{xyz}, K_{xy}, K_x are the hydrodynamic derivatives according to the indicated variables x, y, z, i.e. added mass, damping, etc. Moreover, J_x is the moment of inertia in the roll axis, U is the surge velocity, $\Delta g\rho$ is the buoyancy (Δ draught, g gravitational constant, ρ density of water), $\overline{GM}_T$ is the transversal metacentric height, and $p = \dot{\phi}$ is the roll rate. More information about the coefficients can be found in Perez (2006). The parts K_{ext}, K_c and K_u denote the external forces due to control and disturbance moments, respectively.

Under the ordinary assumptions which can be applied for a system in DP and roll damping, i.e. U = const., small roll angles $\phi < 10°$ and roll rates $p \approx 0$, equation (1) can be simplified and represented as a second order system in the frequeny domain using Laplace operator s

$$G_\phi(s) = \frac{\phi(s)}{K_{ext}(s)} = \frac{K}{s^2 + \alpha_1 s + \alpha_0}$$

where

$$\begin{aligned} K &= \frac{1}{K_{\dot{p}} - J_x} \\ \alpha_1 &= \frac{K_p + K_{|u|p}|U|}{K_{\dot{p}} - J_x} \\ \alpha_0 &= \frac{K_{\phi uu}U^2 + \Delta g\rho\overline{GM}_T}{K_{\dot{p}} - J_x}. \end{aligned} \tag{2}$$

The corresponding transfer function for the roll rate p can be obtained by differentiation $G_p(s) = p(s)/K_{ext}(s) = sG_\phi(s)$.

2.3 VSP for active roll damping

A VSP is a vertically installed propeller that consists of a rotating disk which rotation axis is perpendicular to the water surface. At the outer end of the disk several blades are connected parallel to the rotation axis. During one revolution of the disk, the variable pitch angle of one blade fulfills an overlayed motion. This motion can be influenced to generate a thrust in a desired direction. Along with this, the magnitude of the thrust can be changed by the rotational speed of the disk. The blade pitch can be set nearly step-less within a short time by a lever at the top of the VSP, which makes the thrust generation and maneuvering fast and accurate. Furthermore, the producible forces, in contrast to controllable-pitch propellers, are equal in all directions. Due to the installation of the VSP at the bottom of the ship, lateral forces also induce roll moments. These moments can be altered fastly compared to the ships