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Extended summary

Advanced strategies for control and fault diagnosis of marine surface vessels

Curriculum: Ingegneria Informatica, Gestionale e dell'Automazione

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Abstract. The motion of surface vessels due to waves is significantly affected by environmental disturbances, like waves, currents and wind. The roll-induced high vertical accelerations increase the possibility of cargo damage and the incidence of seasickness development, while horizontal motion due to waves, currents, waves and wind affects the ship offloading and dynamic positioning operation. Thus the design of control systems to damp the induced roll motion and to guarantee a reliable stabilization to fixed or dynamic position, also in case of thruster failure, as prescribed from certification agencies. The main issue is reaching a proper trade-off between the achievable performances and the complexity of the control system in relation to the operating condition and the coupling between the ship degree of freedom. This thesis presents some novel contributions to the quantification of fundamental limitation in roll stabilizing control and a novel variable structure control system focused on the robustness respect to model uncertainties, environmental disturbances and thruster failures specific for rudder-fin-roll-stabilers and dynamic positioning. The proposed solutions are validated using simulation tools and software and experimental tests conducted at the Marine Cybernetics Laboratory of the Norwegian University of Science and Technologies with a scaled model vessel.

Keywords. Ship Motion Control, Fault Tolerant Control, Roll Damping, Dynamic Positioning, Variable Structure Control

1 Problem Statement and Objectives

The motion of marine surface vessels is significantly affected by environmental disturbances. As reported in [1], roll is the largest and most undesirable ship motion component: transverse accelerations due to the roll motion can interrupt the tasks performed by the crew and increase the amount of time needed to complete the mission or even prevent the crew from performing the task at all. Vertical and transversal accelerations induced by the roll motion can contribute to the development of sea sickness in the crew and in the passengers with a consequent comfort deterioration. The induced accelerations may also produce damage in the cargo and limit the possibilities to handle on board equipment. Moreover this motion increase the fuel consumptions during cruise. On the other hand horizontal motion induced by marine currents, waves and wind make it unsafe to anchor or tie up the ship, driving it away from the desired position. This motion can cause collisions and damages to the ship hull, cargo and passengers when the ship is within the same operating area of other vessels or marine vehicles or nearby breakwater in dock area.

Figure 1: (left) Dive Port vessel sitting on Dynamic Positioning and (right) cargo ship experiencing severe roll motion.

Hence the design of reliable and robust motion control systems for roll damping (RD) and dynamic positioning (DP) becomes crucial for the safety of marine operations, as addressed in [2]. A semi-autonomous marine surface vessel can be defined as a ship that can accomplish a task during a cruise without the help of the human guide. A Roll Damping systems for surface vessels is defined as system that maintains the ship roll motion below some bounds for a range of sea conditions without affecting the capability of the vessel to steer. A dynamically positioned (DP) vessel is by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) defined as a vessel that maintains its position and heading (fixed location or pre-determined track) exclusively by means of active thrusters, [3] within some bounds. Thus RD and DP are two examples of tasks that a semi-autonomous surface vessel should accomplish. Over the years the technical feasibility of motion control devices for roll damping (bilge keels, U-tanks, gyrostabilisers, fin, rudder) and the positioning of the surface vessels (mooring lines, anchors, azimuth and tunnel thrusters) has been demonstrated. Most of these devices rely on feedback control systems whose designs have proven to be far from trivial and subject to fundamental performance limitations and trade-offs. Then most of the work shifted to development in control system designs rather than to the development on new concepts and devices [4-5]. The most important contribution to roll damping techniques are reviewed in [1, 5-6], while a comprehensive survey of the past, current and emerging dynamic positioning systems is given in [3]. The present thesis aims to exploit trade-offs and limitations in roll damping control systems [7], develop robust control laws for the stabilization (RD) of the roll motion [8] and the horizontal (DP) motion [9-10] of marine surface vessels with a focus on safety and reliability of the solution. Therefore part of the work aims to develop a fault tolerant scheme to maintain the Dynamic Positioning in case of a failure of one of the ship actuators [11] in order to meet Class 2 DP certification requirements [12].

2 Research planning and activities

In order to provide the mentioned solutions, the first planned activity was to develop mathematical models for the motion of the surface vessels , which is used as a substitute of the real system in simulated scenario (thus referred as plant model) and to implement model-based control and filtering techniques in the experimental scenario (thus referred as control model). The development of the mathematical models is largely based on models already available in the marine control literature [2], adapted to the case of study of the thesis. The resulting model is based on the superposition theory, largely adopted for ship motion control system design [13]. Motion is conceptually decomposed as superposition of three contributions: slowly-varying disturbance motion produced by second-order waves effects, current and wind; wave-induced motion, referred as Wave Frequency (WF) dynamics, where the wave frequency oscillatory motion induced by first-order waves is described by a seakeeping model; control-induced motion described by a maneuvering model, clarifying the relationship between control action and its effects on the motion. This dynamic is very slow compared to that induced by waves for cruise and offshore supply vessels addressed by this thesis, therefore the ship control-induced dynamics is also called Low Frequency (LF) dynamics. Referring to Figure 1, the three contributions to the motion are respectively described in a local geographical inertial North-east-down frame, fixed to the Earth, an inertial hydrodynamic frame not fixed to the ship hull, which moves at the average speed (zero speed is a limit) of the vessel) and a non-inertial body-frame fixed to the ship hull and centred to the intersection of the principal axis of inertia. Kinematics transformations are used to express the coordinates from a frame to another. Potential theory is used to describe the sea motion, and the Motion Response [2] Amplitude Operators (RAO) [14] to calculate the ship motion response to first-order and second-order wave disturbances. The resulting model is a 6 degree of freedom (DOF) non-linear coupled model of equations [15]. The 6DOF general model is adapted for ship roll damping applications from [1, 5-6, 16] to a 3 DOF model considering only the sway-roll-yaw coupling, obtaining a simplified control linear model in [7] and a non-linear model [8], whereas the 3 DOF model used for the DP application in [9-11] comprises only the horizontal motion components (surge, sway, yaw) as suggested in [3, 17].

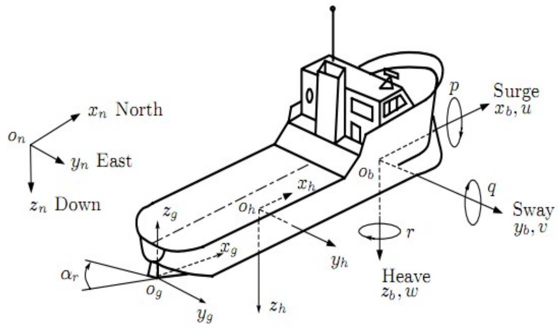

Figure 2. Ship reference frames

3 Analysis and discussion of main results

Among the roll damping devices, rudder is often preferred to produce a roll moment, which can counteract the one induced by the waves, because it is a relative inexpensive solution, being already present on any ship, it does not require extra-space or extra-weight on the boat and it can be combined with other roll damping devices. The use of the rudder for roll damping and heading control introduces trade-offs in the control scheme. A reduced order (sway, yaw, roll) model and coupling are exploited in [18]. The Linear Time Invariant system of the roll dynamics shows an inverse response and non-minimum phase dynamics due to a right-half plane zero. An innovative Poisson integral approximation is proposed to find suitable links between design specifications and fundamental limitation of linear rudder roll damping regulators. The theoretical results reported in [7] show a better approximation of the Poisson integral previous works [19-20] and confirm that roll damping is achievable within delimited frequency ranges, but lead to roll amplification in low and high frequencies, which is a function of the right half plane zero.

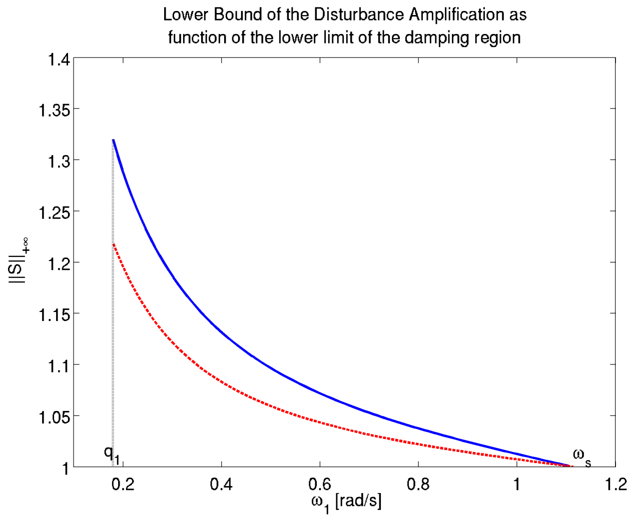

Figure 3: Lower bound of the magnitude of the maximum amplification of wave disturbances as function of the specifications on the banwith of the damping region presented in this work (blue line) and in a previous work (red line) from [20]. ω_s is the frequency value of the maximum damping, q_1 is the right-half plane zero of the roll dynamics transfer function.

These results are used to derive control specification and to design a loop shaping controller, where parameters are function of the desired specs and adaptable to sea conditions showing better performances than state-of-the art Minimum Variance Cheap Control, as reported in Table 1. In order to overcome trade-offs due to rudder roll damping the use of an external device (fin stabilisers) is first proposed in [8] and further developed in the thesis. An integrated control system for heading and roll damping of a multipurpose naval vessel by means of active fins and rudder has been investigated. A multivariable nonlinear model which takes into account the hydrodynamic couplings among sway, roll and yaw due to both the wave effect and the control devices has been considered. A stability analysis of the zero dynamics for the proposed nonlinear model along with the design of a MIMO variable structure control law has been performed. Using Lie derivatives and nonlinear state transformation it is demonstrated that the coupled non-linear system shows stable zero dynamics when wave disturbances are bounded. Computer simulations performed for the marine vessel in [1],[21] are carried out to validate the proposed variable structure sliding control show that the yaw dynamics is less influences to roll damping compared to a rudder-only approach.

Table 1. Roll Damping Control System Performances

Reduction of Roll: $RR(\varphi)=100\cdot(1 - rms(\varphi_{cl})/rms(\varphi_{ol}))$			
Direction of the waves relative to ship	45°	90°	135°
Minimum Variance Cheap Control	18.50%	20.79%	22.96%
Optimised Loop Shaping Control	20.4%	51.4%	57.23%
Optimised Loop Shaping Control Control Effort Weight	40.34%	56.73%	60.79%

The variable structure control is proposed also the control scheme for the solution of the dynamic positioning problem: maintain the position and orientation of the ship fixed or according to a slow reference track regardless the environmental disturbances, thruster disturbances and failure. A stable two-step sliding surface as function of the tracking error (surge velocity, sway velocity, yaw rate) is proposed. The stability of the switching control law which takes into account uncertainties in the model parameters from their nominal values as well input disturbances and thruster failures is demonstrated, proving that the discrete-time sliding mode existence condition [22] is satisfied. Position and orientation tracking error accuracy is improved by an integral term in the control law. A fault diagnosis module detects and isolate thruster failure to meet DP Class II requirements, using Parity Space and Luenberger Observer residuals, a reconfiguration module switch the control law dynamically allocating thruster forces. Computer simulations are carried out using simulation tools and software and experimental tests conducted using the Cybership III, the scale model of an offshore supply vessel at the Marine Cybernetics Laboratory of the Norwegian University of Science and Technologies (Trondheim, Norway). The switching control law show robustness to changing sea conditions and uncertainties of model parameter (e.g. load distributions and inertia) as reported in Table II.

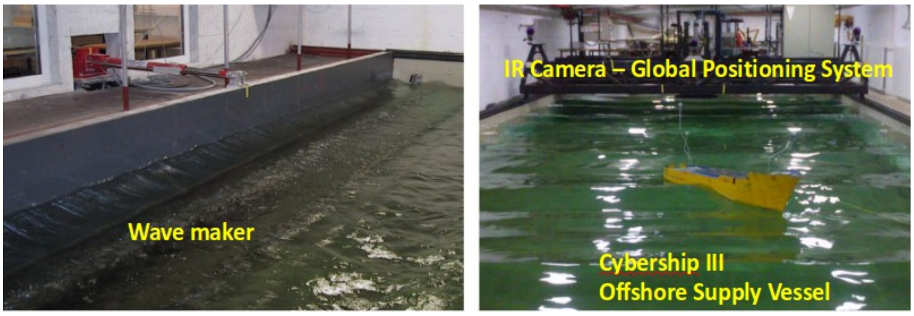

Figure 4: Experimental setup

Table 2. ISE performance comparison between DTVSC and PID controller along 3DOF in different operating condition

	ISE index		
DOF	DTVSC	PID	Difference
	Fixed Position		
n	0.0291	0.0291	-1.23E-3%
e	0.0291	0.0291	-1.26E-3%
φ	6*10^(-5)	6*10^(-5)	-1.14E-3%
	Reference Trajectory		
n	0.058	0.357	-84%
e	0.0582	0.7293	-92%
φ	0.0001	0.0623	-99%
	Increase of inertia parameter 20%		
n	0.1187	0.4771	-75%
e	0.0666	0.8036	-92%
φ	0.0036	0.1226	-97%

4 Conclusions

In this work, the design of robust and safe control systems for roll damping and dynamic positioning of marine surface vessels have been addressed. The main issue in feedback control using control surfaces like the ship rudder is that trade off arise between achievable performances, control effort limitations and intrinsic limitation of the model. Key results are the investigation of how performance limitations can affect the control design, resulting in optimised control with better performances for roll damping. The variable structure control approach adds a degree of robustness to the system resulting better performance of integrated heading control and rudder damping and stable dynamics of dynamic positioning, as demonstrated in this thesis. Simulation and experimental results have been carried out to corroborate the theoretical analysis and comparative tests with PID control confirm the validity of the approach. A validation of the proposed mathematical analysis for several parameters data-set describing different operative conditions for different vessels could be performed in the future along with the design of an unified integrated framework for seakeeping with both-roll damping and dynamic positioning capabilities.

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