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Complex Motion Control System of a Cargo Ship in All Phases of a Sea Voyage

Summary of the dissertation

The evolution of the concept of a sea-going cargo ship in recent years has focused on the development of vessels that will be able to carry out voyages with limited involvement of a human operator or eventually fully autonomously. This task reveals its complexity in many aspects: economic, legal, social, technological and even ethical.

One of the key technological issues is the construction of the ship's motion control system that will ensure efficient and safe steering of the ship in all stages of the sea voyage. Functional analysis of the tasks to be performed by this control system leads to their division into three levels:

- The layer of management (strategy) in which, based on the recommended economic parameters, weather forecast and the owner's decisions, the travel route is planned;
- Supervisory navigation system, which, on the basis of information from the management layer and navigation devices, such as the electronic map and the anti-collision system, determines the safe trajectory of the ship's voyage and on its basis calculates inputs for the control system;
- A control system that determines the input signals to the ship's steering and propulsion devices to keep the motion of the ship possibly close to a trajectory determined in the navigation system.

The parameters taken into account and the data processed in particular layers may differ depending on the type of waters area which the ship is passing. In this context, three phases of full sea voyage, relevant from the point of view of the control system, have been defined:

- Low speed maneuvers in a harbor;
- Passing confined waters with varying speeds;
- Moving in open seas with operating speed.

The different nature of the maneuvers in each of these phases and the significant non-linearities of the ship's dynamics, especially when moving at low speeds, make the synthesis of the control system for an autonomous ship a difficult task.

The purpose of the dissertation was to test the usefulness of a system of switchable regulators to control the motion of a cargo ship during the subsequent stages of a sea voyage: "from quay to quay". Additionally, the effectiveness of using bumpless transfer (BT) techniques in this system was considered in order to limit rapid changes of control signals during switching of controllers.

The research was carried out using the isomorphic model of the LNG carrier of 113 500 DWT built in 1:24 scale, driven by two pulling azipods. This model is used on a daily basis for courses for pilots and deck officers training at the Shiphandling Center of the Foundation for Safety of Navigation and Environmental Protection in Iława-Kamionka, hence it is also called in the dissertation “a training ship”.

The following technologies were used in the process of the synthesis of the control system:

- For the harbor navigation regime (slow speed) – the MIMO controller of longitudinal, lateral and angular velocities of the vessel designed using the technique of linear matrix inequalities – LMI. This controller was adapted from an existing application that had been built to control the isomorphic model of a VLCC tanker;
- For operation in confined waters (variable speed) – the adaptive PID controller using the "gain scheduling" technique;
- For open sea navigation (operational speed) – the MPC predictive controller, which was previously used to control the model of the LNG carrier in the "underway replenishment" (UNREP) maneuver with limited speed. This system was adapted to the role of a trajectory tracking controller for a ship sailing at full speed.

As a result of the characteristic's analysis of the obtained controllers set, it was found that the natural procedure of bumpless transfer in this system would be the method of tracking the output of the active controller, and this routine was used to switch between PID-GS and MPC controllers. The mode of using the MIMO LMI controller to steer the vessel in low speed maneuvers did not require the BT techniques.

The control system was designed and implemented in the MATLAB-Simulink environment. The real-time control platform was an industrial PC. The software was generated using Simulink Coder and Simulink Real Time toolboxes. The properties of the control system were verified in two ways:

- In "Hardware-In-the Loop" (HIL) simulation mode. At that mode, the control system was coupled with a simulator of the LNG carrier model dynamics run on a separate machine in the real-time regime;
- In experiments on the actual training vessel on the lake at the Shiphandling Center.

The individual controllers were tested separately. The parameters of the input trajectories for a given controller were specified to correspond to the vessel motion conditions in the appropriate voyage phase. The influence of the BT system on the amplitude and rate of change of the azipods rotation angle during the controllers' transfer was also investigated. Finally, the control system was tested during the autonomous cruise on the lake. Input trajectory designed for this experiment included all phases of the journey "from quay to quay".

The research has shown that:

- The component controllers: LMI, PID-GS and MPC properly controlled the motion of the isomorphic model of the LNG carrier in the voyage phases dedicated to them;
- The bumpless transfer system reduced both the amplitude and the rate of changes in the angle of rotation of the pod thrusters during the switching of controllers;
- A complex control system build using three switchable regulators can safely control the isomorphic ship model at all stages of the "quay to quay" voyage.

At the same time, the outcome of the research indicated the directions of development of the control system and possible new research areas:

- The LMI controller, although working properly, requires improvement, especially in the control of angular velocity channel. The algorithm of determining its input signals, is based on the values of static errors of ship position related to the way-point. It is the source of the extended harbor man oeuvres;
- The isomorphic model of the LNG carrier is not able to operate in different loading conditions, therefore the control system was checked in a "full load" state only. Similarly,

due to the nature of the lake area, the control system was not tasted when the model was moving in waves. Further research in this scope seems necessary.

- Although the bumpless switching system reduces the amplitudes and the rate of change of the control signals, it cannot be decided that its application in ship motion control systems is justified.

The structure of the dissertation

The dissertation has been divided into four chapters. The first one places the technology used in the investigated system against the background of a short history of the ship motion control development. It also contains the analysis of the stages of a complete sea voyage. Based on this study, it was determined that, at the level of the control systems, voyage can be divided into the above-mentioned three phases. The features of the bumpless switching systems were also analyzed, and the system selected for implementation was described.

The second chapter is a detailed description of the control object – the isomorphic model of the LNG carrier *Dorchester Lady*. It shows all the navigation, steering and propulsion devices installed on the model. The configuration of the measurement and control system, which was used during experiments in the real environment, was also described. The chapter ends with the characteristics of the waters areas and facilities available on the lake during the tests.

The third chapter presents the details of the synthesis and implementation of the controllers that make up the control system. It also describes the implementation of the BT system. Subsequent components of the control system are presented in the form of Simulink diagrams supplemented with a description of their main blocks.

The fourth chapter contains the results of experimental research. The results of tests for individual controllers are presented, then for the BT system and for the complete voyage "from quay to quay". The courses of the relevant trajectories and recorded signals were summarized in pairs: for the HIL simulation and for experiments carried out with the isomorphic model in similar weather conditions. In this chapter, an analysis of the performance of individual components of the control system, using the control quality indicators set for subsequent tests, was also carried out.

Finally, conclusions and proposals for further work arising from the analysis of the results are presented.

The dissertation is supplemented by an appendix describing the multidimensional, non-linear mathematical model of the dynamics of the training ship Dorchester Lady. This model was used to simulate the control object, both at the initial stage of designing individual elements of the control system and during the verification of the complex control system in the HIL mode.

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