An Effective Adaptive Autopilot for Ships

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Abstract: Ship motion is a complex controlled process with several hydrodynamic parameters that vary in wide ranges with respect to ship load condition, speed and surrounding conditions (such as wind, current, tide, etc.). Therefore, to effectively control ships in a designed track is always an important task for ship masters. This paper presents an effective adaptive autopilot for ships that ensure the optimal accuracy, economy and stability characteristics. The PID control methodology is modified and parameters of a PID controller is designed to satisfy conditions for an optimal objective function that comprised by heading error, resistance and drift during changing course, and loss of surge velocity or fuel consumption. Designing of the controller for course changing process is based on the Model Reference Adaptive System (MRAS) control theory, while as designing of the automatic course keeping process is based on the Self Tuning Regulator (STR) control theory. Simulation (using MATLAB software) in various disturbance conditions shows that in comparison with conventional PID autopilots, the designed autopilot has several notable advantages: higher course turning speed, lower swing of ship bow even in strong waves and winds, high accuracy of course keeping, shorter time of rudder actions smaller times of changing rudder direction.

Keywords: PID control, adaptive control, MRAS, STR, ship autopilot

1. INTRODUCTION

Autopilot is one of the most important equipments used in ships. Autopilots are not just used to lead the ship on a desired trajectory, but also to raise the safety level of the journey and control the ship economically. An optimal autopilot can shorten 3-5% length of the journey and therefore, reduce the fuel consumption, especially in bad whether conditions. A good autopilot can help to avoid undesired situations on maneuvering and remarkably reduce the numbers of ship operators. In the last decades, taking advantages of drastic development of micro-electronics and control theory several new and effective methods have been proposed and developed for designing Ship Autopilots [1], [2], [3]. Ship Autopilots designed based on the PD and PID controllers are simple, reliability and easy to construct, however their performance in various environmental conditions is not as good as desired. Therefore, ship Autopilots with PD or PID controllers are usually required aids from operators to adjust controllers' parameters corresponding to navigating conditions. This study concentrates on design of ship autopilots based on adaptive control theory and optimal control theory. Several maneuvers' simulations have been carried out using MATLAB software to verify the effectiveness of the method, and excellent results achieved show remarkable advantages of the ship autopilot in comparison with other conventional autopilots such as PD or PID ones.

The paper is organized as follows: The first session gives the nature of the problems considered, previous works, purpose and contribution of this study as well as related research. The second session presents the mathematical model used in this study to express ship steering motion. The model contains both linear and non-linear features of ship steering. Control algorithm used for the adaptive autopilot and designing issues are presented and discussed in details in the third session. To verify the effectiveness of the adaptive autopilot, MATLAB software was used to simulate ship motion during several different maneuvers. Session 4 gives simulation results, including comparison of the quality of a conventional PID autopilot and the adaptive autopilot. And finally, the fourth session draws some conclusions form this study and points out some possible direction for further study.

2. MATHEMATICAL MODEL

The mathematical model used to express ship motions in this study is as follows [4], [5], [6], [7], [8], [9], [10]:

$$T_r(dr/dt) + H_r(r) = K_r\delta + K_r^{'}\delta \tag{1}$$

$$T_u(du/dt) + H_u(u) = K_u r^2 \tag{2}$$

$$v + H_v(r) = 0 \tag{3}$$

$$r = d\Psi_L / dt \tag{4}$$

$$\Psi = \Psi_L + \Psi_H \tag{5}$$

, where: T_r, T_u, K_r, $K_r^{'}$, K_u are ship hydrodynamic parameters depending on ship speed on the course, load condition and weather conditions such as waves, winds, tidal, water depth and so on;

δ is rudder angle;

$K_\delta^{'}$ expresses deflection due to winds and tidal;

Ψ , $K_r^{'}$, $K_r^{'}$ are ship heading, ship heading in no noises conditions and ship heading in high noises condition, respectively;

u , v , r are ship surge, sway and yaw velocities, respectively;

H_u, H_v, H_r are functions that express the nonlinearity of the system corresponding to u , v , r , respectively. In general, they have the following form:

$$H_a(a) = k_3a^3 + k_2a^2 + k_1a + k_0 \tag{6}$$

k_0 shows the non-symmetry of the ship (k_0 = 0 means the ship is ideal symmetric), k_1 = 1 for stable ships and k_1 = -1 for non-stable ships;

Usually, in order to avoid the influences of ship speed and dimension, the above equations are expressed in a non-dimensional form by multiply the parameters, coefficients with following non-dimensional coefficients:

$$r^* = (L/u)r\,;\; v^* = v/u\,;\; u^* = (u/U_0) \tag{7}$$

, with L and U_0 are ship length and speed, respectively.

Then, the above equations (1) - (5) can be re-written as follows:

$$T_r^*(L/u)(dr^*/dt) + H_r(r^*) = K_\delta^*\delta + K_r^{'*}\delta \tag{8}$$

$$T_u^*\,(L/u)(du^*/dt) + H_u(u^*) = K_u^* r^{*2} \tag{9}$$

$$v^* + H_v(r^*) = 0 \tag{10}$$

$$\Psi = \Psi_L + \Psi_H \tag{11}$$

3. CONTROL ALGORITHM

Usually a conventional PID autopilot is used, and the control signal δ has the following form:

$$\delta = K_p(\Psi - \Psi_r) = K_d(d\Psi/dt) + K_i\int_0^t(\Psi_r - \Psi)dt \tag{12}$$

, where Ψ_r is reference (desired) heading, K_p , K_i , K_d are coefficients adjusted by ship operators according to ship speed, load and weather conditions and so on.

In good weather conditions, this kind of autopilots may work rather well (with not so high technical and economical characteristics). But in bad weather conditions (with presence of waves, winds, tidal, etc.), ship hydrodynamic parameters will vary in large scale, then this kind of autopilots shows tremendous disadvantage and in many cases, even integration and differentiation terms should be excluded. This will result in rocking of the ship and the rudder has to work with high frequency, that reduces durability of the steering systems. A method to overcome this disadvantage is to create non-sensitive zones, but it causes large deflection in ship course and hence requires large fuel consumption.

This paper presents another method to solve those problems, that is using optimal control algorithms to automatically the controller's parameters corresponding to the above-mentioned conditions (ship speed, load conditions, tidal, waves, winds and so on). The optimal control function is as follows:

$$J = \min\left\{(a/T)\int_0^T((\Psi_r - \Psi)^2 + l_1 r^2 + l_2\delta^2)d\tau\right\} \tag{13}$$

In this formula, the first term expresses heading error $e = \Psi - \Psi_r$, the second term expresses the influence of resistance and deflection during course turning process, and the third term expresses loss of ship speed and hence, the fuel consumption. In this study, the steering system is divided into 2 different processes with following characteristics:

Course changing process: In this process, economy plays a very modest role, but the most important is the accuracy of the heading after course changing process. Therefore, l_1 , l_2 should have rather small values. Usually, 2 types of course changing are use, one is course changing with constant ship turning rate and the another is course changing with constant turning radius.

Here, the autopilot is designed based on application of Model Reference Adaptive System (MRAS) and the controller's parameters have the following forms [11], [12], [13], [14], [15]:

$$K_p = K_{p0} + \gamma_1\int_0^t(p_{12}e + p_{22}\dot{e})(\Psi'' - \hat{\Psi})d\tau \tag{14}$$

$$K_d = K_{d0} + \gamma_2\int_0^t(p_{12}e + p_{22}\dot{e})\hat{\Psi}d\tau \tag{15}$$

$$K_i = K_{i0} + \gamma_3\int_0^t(p_{12}e + p_{22}\dot{e})d\tau \tag{16}$$

, here $\hat{\Psi}$ is the estimated heading, γ_i (i = 1, 2, 3) are self tuning coefficients.

Automatic course keeping process: This process should be divided into 2 different cases: (1) Common case: when the ship running on the sea, then the economy plays an important role, therefore l_1 , l_2 should have rather large values; (2) when the ship running in rivers, narrow channels or on confined water conditions, where the accuracy of course keeping is much more important than the economy features, therefore l_1 , l_2 have rather values as in course changing process.

In this process, the autopilot is designed based on the Self tuning Regulator (STR) with following parameters of estimator:

$$(K_m^*/T_m^*) = (K_m^*/T_m^*)_0 - \gamma_1\int_0^t e(\delta - K_{im})d\tau \tag{17}$$

$$(1/T_m^*) = (1/T_m^*)_0 + \gamma_2\int_0^t e\dot{\Psi}_m d\tau \tag{18}$$

$$K_{im} = -\gamma_3\int_0^t e\,d\tau \tag{19}$$

Hence, the controller's parameters are as follows:

$$\delta_r = K_p(\Psi_r - \hat{\Psi}) - K_d\hat{\Psi} + K_i \tag{20}$$

$$K_p = (z/2)(U_0/U)\,;\; 0.5 < 2.5\,\xi < 5.0 \tag{21}$$

$$K_d = (L/U)(\sqrt{(1 + 2K_p K_m^* T_m^*)} - 1)/K_m^*)$$

$$U = \sqrt{u^2 + v^2}\,;\; K_p < K_d < K_p L/U \tag{22}$$

$$K_i = K_{im}^{'} \tag{23}$$

, here z is the optimal coefficient, $1 \le z \le 5$, z = 1 for accuracy optimal case and z = 1 for economy optimal case, subscript m denotes parameters of the estimator, $K_{im}^{'}$ is average value of K_{im} .

4. SIMULATION RESULTS AND ANALYSIS

To verify the effectiveness of the new adaptive autopilot, the presented autopilot system has been simulated using MATLAB software. Several different ship maneuvers have been carried out, including course keeping, course changing processes and their combination. This session gives simulation results of a maneuver that the ship begins from zero heading angle changes its course to -23 deg., runs straight about 10 minutes, then change its course to 15 deg and finally keeps a straight course.

Figure 1 shows ship heading angles produced by the conventional PID autopilot and this adaptive autopilot during this maneuver. From this figure, the adaptive autopilot controls the ship rather well and the ship following the reference track much better than the PID autopilot case.

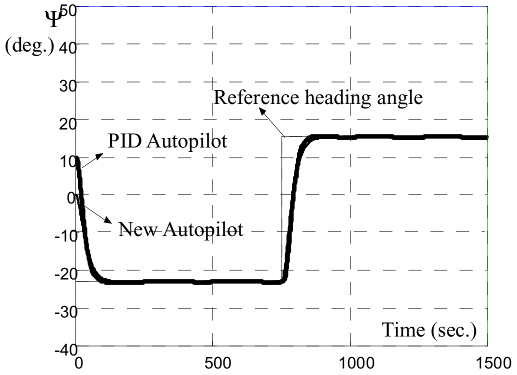

Fig. 1 Comparison between heading angle of PID autopilot and new autopilot in a maneuver

To consider the quality of the control processes, errors of ship heading angle for both PID autopilot and the adaptive autopilot are simulated and drawn in Figure 2. This figure shows clearly that the overshoot values of the new adaptive autopilot in course changing processes were reduced about 2 times compared to corresponding values of the PID autopilot.

Variation of parameters K_p , K_i , K_d during the above described maneuver are plotted in Figure 3. This figure shows that the autopilot adapted rather well with both the course changing and course keeping processes: in the course keeping process, the control parameters were kept almost at constant values, while as in the course changing process, the control parameters were changed accordingly. That proves the effectiveness of the adaptive autopilot in course keeping and course changing process as analyzed in session 3.

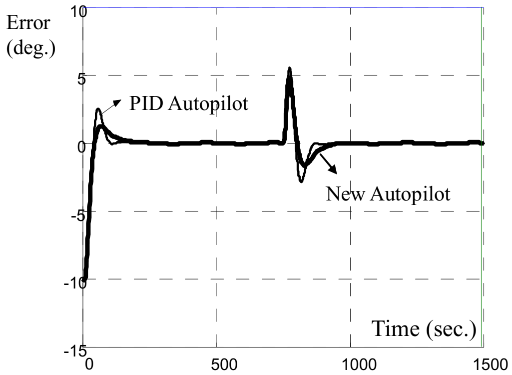

Fig. 2 Comparison between heading errors of PID autopilot and new autopilot in a maneuver

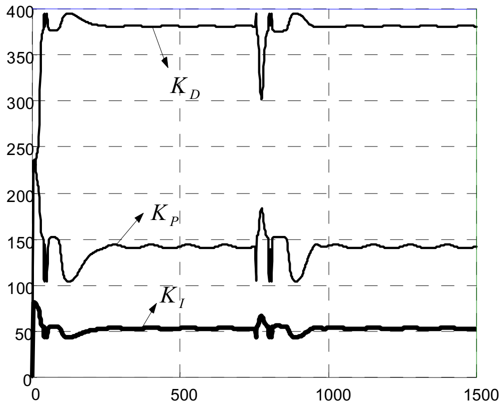

Fig. 3: Variation of control parameters of the new autopilot during the maneuver

5. CONCLUSIONS AND FUTURE WORKS

An effective adaptive autopilot for ships that ensures the optimal accuracy, economy and stability characteristics has been presented and its design issues have been discussed. The PID control methodology has been modified and designing of the controller for course changing process is based on the Model Reference Adaptive System (MRAS) control theory, while as designing of the automatic course keeping process is based on the Self Tuning Regulator (STR) control theory. Simulation (using MATLAB software) shows that in comparison with conventional PID autopilots, the designed autopilot has several notable advantages: higher course turning speed, lower swing of ship bow even in strong waves and winds, high accuracy of course keeping, shorter time of rudder actions smaller times of changing rudder direction.

The new ship autopilot is expected to have several important features, however, to be able to construct a real ship autopilot of this type, many further studied should be carried out. Among them some can be pointed out here. First is consideration of strong environment disturbances such as tidal and currents. Second is choosing proper control parameters. Third is full consideration of an automatically design process. And finally, the autopilot should be put into real ships for practical use and correction.

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