SHIP STEERING

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Summary

This article describes automatic steering of ships. Particular attention is given to automatic control of a ship's course. Roll stabilization and track keeping are also briefly described. The control of a ship can be seen as an optimization problem. Optimum performance is achieved by proper tuning of the autopilot parameters and by properly taking care of the disturbances.

The earliest autopilots used PID-controllers with gains that were adjustable by the users. In recent years adaptive autopilots that automatically adjust for changing circumstances have been developed. These autopilots are based on relatively simple models of a ship and the disturbances. Kalman filter theory can be used to derive algorithms for optimally suppressing undesired rudder motions caused by relatively high frequency wave motions.

1. Introduction

Automatic steering of a ship from one place to another along a planned track is, in principle, a track-keeping problem. Given the desired track, the heading of the ship (and eventually its speed) should be such that the distance from the desired track is minimal. In most situations track keeping is still done manually by the navigator. On a sea-going ship the navigator determines a constant heading that should be steered. For special operations, such as mine hunting and hydrographical survey, automatic track-keeping systems are used.

For inland ships, sailing on winding rivers, it is the rate of turn that is being controlled. Heading control and rate-of-turn control can be done manually by the person at the helm or automatically by an autopilot. In the case of manual control the helm adjusts the rudder angle. Mostly the rudder has its own (automatic) control loop, but especially on inland vessels, the operator may use on–off signals that cause the rudder to move with a constant speed to port or starboard. Autopilots for heading control are nowadays standard on most sea-going ships. Where reduction of roll motions is required (e.g., on naval ships for helicopter operations and on passenger ships to improve the comfort) roll-stabilization systems are used as well. Because the heading-control loop and the roll-control loop interact, a multivariable design would give the best results, but in most commercial systems two independently designed control systems are present. The rudder is used for control of the heading and fins or tanks are used to reduce the roll. Because the two loops interact it is possible to use the rudder for heading control as well as for roll reduction.

Such systems are called rudder roll stabilization systems. Another special type of operation is dynamic positioning, used, for instance, in the offshore business. A dynamic positioning system uses a number of thrusters to maintain a vessel’s position and orientation under the influence of disturbances, such as wind, waves, and current. Underwater vessels also require, besides the before-mentioned control loops, a depth controller. Automatic berthing is still an area of research. In all the other areas automatic controllers are widely applied and development of more advanced control algorithms continues. Dealing with nonlinear dynamics, disturbances of wind, waves, and currents, and minimizing fuel consumption form the major challenges for researchers.

1.1. History

Automatic steering of ships has a long history. As early as 1922 Minorsky and Sperry reported on automatic steering devices for ships, at a time when there was hardly a control-theory basis. The early autopilots of a purely mechanical construction provided only a very simple steering action: rudder was given proportional with the heading error. To prevent an oscillatory behavior, a low controller gain had to be selected. This made the autopilot useful only during course keeping in situations where relatively little accuracy was required. Introduction of a PID algorithm greatly improved the potential performance, and for a long time all makes of autopilots were based on this algorithm. Replacement of the purely mechanical devices by electronic equipment made the autopilots more flexible. These PID-type autopilots are difficult to adjust manually. The number of controller settings is large and there is no clear relation between the settings and the operational demands or the environmental changes. Because of the need of automatic parameter adjustment, ship steering was one of the first areas where adaptive and fuzzy controllers were successfully applied. From 1970 onwards, several adaptive autopilot designs were reported. The earliest adaptive autopilots were based on a model-reference approach and on self-tuning regulators. Also fuzzy autopilots and autopilots based on H_∞ and LQG controllers have been described in the literature.

2. Modeling

Modeling of a ship is of interest for the design of the ship as well as for the design of the control system. For ship design often rather complex hydrodynamic models are being used. The parameters of these models can be obtained by measuring hydrodynamic coefficients from scale models. Simplifying or rewriting the hydrodynamic models can yield the generally much simpler models for designing autopilots. The parameters of the latter can often be obtained from full-scale experiments.

In the most general case a ship can move in six degrees of freedom: translations in the *x*-, *y*-, and *z*- directions, and rotations around these axes. For surface ships it is common practice to consider only motions in the horizontal plane. This reduces the number of degrees of freedom to three:

motions in the *x*-direction (“surge”)
motions in the *y*-direction (“sway”)
rotations around the *z*-axis (“yaw”)

In Figure 1 and Table 1 the coordinates and variables that play a role in the modeling process are defined.

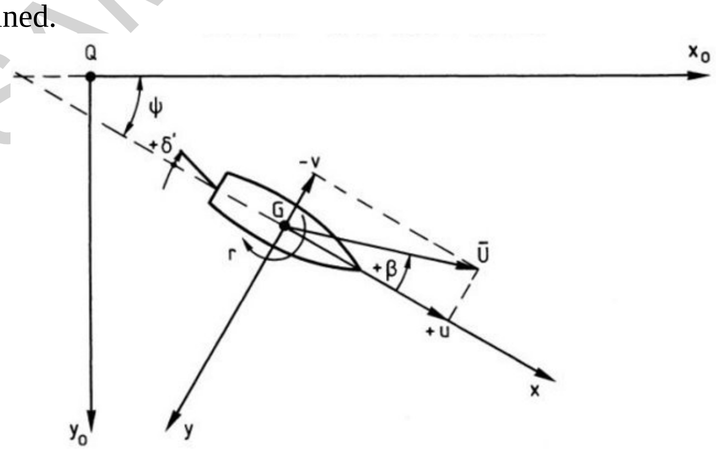

Figure 1. Definition of motions in the horizontal plane

The basic equations of motion are obtained by writing Newton's laws in a space-fixed coordinate system:

$$m\frac{d^2x_0}{dt^2} = X_0 \tag{1}$$

$$m\frac{d^2y_0}{dt^2} = Y_0 \tag{2}$$

$$I_{zz}\frac{d^2\psi}{dt^2} = N \tag{3}$$

To determine the influence of forces and moments directly acting on the hull of the ship, a ship-fixed coordinate system is more convenient. Transformation of Eqs. (1) to (3) yields:

$$m\left(\dot{u} - vr\right) = X \tag{4}$$

$$m\left(\dot{v} + ur\right) = Y \tag{5}$$

$$I_{zz}\dot{r} = N \tag{6}$$

where *X* and *Y* are the summations of all the forces in the *x*- and *y*- directions, which act on the hull of the ship, and *N* is the moment caused by these forces. It is not easy to determine the relationship between *X*, *Y*, and *N*, and all the variables involved.

x_0, y_0	space-fixed coordinate system
x, y	ship-fixed coordinate system
ψ	course angle or heading
$r = \dot{\psi} = d\psi / dt$	rate of turn or course-angular velocity
δ'	rudder angle
β	drift angle
G	ship's centre of gravity
$\bar{U} = u - v$	instantaneous speed vector
$u = dx / dt$	speed in forward direction
$v = dy / dt$	drift or sway speed
X_0, Y_0	forces in the $x_0 -$ or $y_0 -$ direction
X, Y	forces in the *x*- or *y*- direction
N	moment with respect to the *z*-axis
M	mass of ship
I_{zz}	moment of inertia with respect to the *z*-axis

Table 1. Definition of variables

2.1. Hydrodynamic Models

In general, approximations are made by writing, for example:

$$N = f\left(u, \dot{u}, v, \dot{v}, r, \dot{r}, \delta', \dot{\delta}', u^2, v^2, r^2, \ldots\right) \tag{7}$$

Expansion of this equation into a Taylor series yields:

$$\begin{aligned} dN = & \frac{\partial f}{\partial u}u + \frac{\partial f}{\partial \dot{u}}\dot{u} + \frac{\partial f}{\partial v}v + \frac{\partial f}{\partial \dot{v}}\dot{v} + \\ & + \frac{\partial f}{\partial r}r + \frac{\partial f}{\partial \dot{r}}\dot{r} + \frac{\partial f}{\partial \delta'}\delta' + \frac{\partial f}{\partial \dot{\delta}'}\dot{\delta}' + \text{higher - order terms} \end{aligned} \tag{8}$$

where the small variations Δu are denoted as *u*, and so on.

When the “hydrodynamic derivatives” are denoted as, for instance:

$$\frac{\partial f}{\partial u} = N_u \tag{9}$$

Eqs. (6) and (8) can be rewritten into:

$$I_{zz}\dot{r} = N_u u + N_{\dot{u}}\dot{u} + N_v v + N_{\dot{v}}\dot{v} + N_r r + N_{\dot{r}}\dot{r} + N_{\delta'}\delta' + N_{\dot{\delta}'}\dot{\delta}' \tag{10}$$

Similar expressions can be written for Eqs. (4) and (5). By taking into account the symmetry of the ship the equations can be simplified. The complexity of the model further depends on the phenomena to be described. For small variations linear models suffice, but for large signals the models have to be extended with nonlinear terms. A simple linear model, known as the model of Davidson and Schiff, is:

$$m\left(\dot{v} + ur\right) = Y_{\delta'}\delta' + Y_v v + Y_{\dot{v}}\dot{v} + Y_r r + Y_{\dot{r}}\dot{r} \tag{11}$$

$$I_{zz}\dot{r} = N_{\delta'}\delta' + N_r r + N_{\dot{r}}\dot{r} + N_v v + N_{\dot{v}}\dot{v} \tag{12}$$

Assuming the forward speed constant, the equation in the *x*-direction vanishes. Use of scale models in a towing tank enables the hydrodynamic derivatives to be measured independently of each other. When the expansion of the Taylor series is carried out further and nonlinear terms are introduced as well, more complex models are obtained.

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Biographical Sketch

Job van Amerongen studied Electrical Engineering at Delft University of Technology, the Netherlands, where he obtained a M.Sc. degree in 1971 and a Ph.D. degree in 1982. From 1971 to 1973 he did his military service as an officer in the Royal Netherlands Navy. From 1973 to 1987 he was assistant and associate professor at the Control Laboratory of the Faculty of Electrical Engineering of Delft University of Technology, where he worked on applications of modern control theory, especially model-reference, adaptive-control in ship-control systems, and electrical-power production systems.

Since 1987 Dr van Amerongen has been Professor in Control Engineering in the Faculty of Electrical Engineering at the University of Twente, the Netherlands. From 1994 to 1998 he was Dean of the Faculty of Electrical Engineering. His current research interests are applications of modern control theory, especially intelligent control, in mechatronic systems, modeling and simulation of dynamical systems, and embedded control systems. He is Scientific Director of the Drebbel Institute for Mechatronics. He is a member of the IFAC Technical Committee on Mechatronics and the IFAC TC on Marine Systems.

Dr van Amerongen is the author and coauthor of many papers on adaptive and intelligent control systems, mechatronics, and automatic steering of ships; coauthor of a book on adaptive control systems; and author of three courses on systems and control of the Dutch Open University.