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Abstract

A simple version of the shipsteering problem is given as a design problem for the VDI/VDE working group on new theoretical design procedures in automatic control. The problem can also be useful in teaching.

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1. INTRODUCTION

Ship steering is a classical example of control. This note presents the ship steering problem in a simple setting. The control variable is the rudder angle. The purpose of control is to make the ship keep a specified heading or a specified path. The heading angle is measured and sometimes also the yaw rate.

The dynamics of a ship changes with speed, trim and depth. A ship can be unstable in certain operating conditions. The ship is influenced by disturbances due to wind, waves and currents. There are disturbances in the measurements. The heading has a finite resolution. Both the heading and the yaw rate are influenced by the motion of the ship.

There are many different requirements on a control system for ship steering. The system must primarily make it possible to operate the ship in a safe way. This means that the closed loop system must be stable with reasonable damping and response. Secondly it is desired that the steering losses are small. Steering losses are generated if the ship motion deviates too much from a straight line course. The coupling between transverse velocity and turning rate gives an average breaking force. Deflections of the rudder also give rise to losses. A good control system should satisfy the requirements of safe economic operation over all possible operating conditions. The robust control problem is to find a fixed feedback which satisfies all the requirements.

2. SHIP DYNAMICS

The ship dynamics is obtained by applying Newton's equations to the ship's motion. For large ships the motion in the vertical plane can be separated from the other motions. It is customary to describe the motion using the coordinates shown in Fig. 1. The equations of motion are then given by

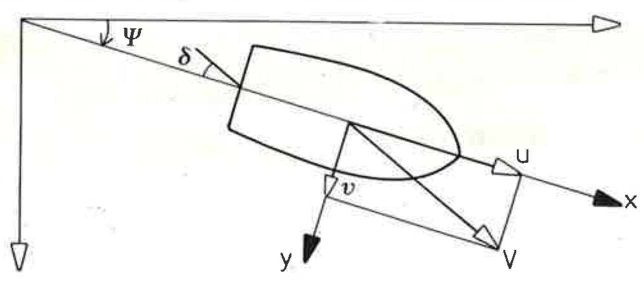

Fig. 1 Coordinates and notations used to describe the equations of motion.

$$\left.\begin{aligned} m\left(\frac{dv}{dt} + ru_0 + x_G\frac{dr}{dt}\right) &= Y, \\ I_z\frac{dr}{dt} + mx_G\left(\frac{dv}{dt} + ru_0\right) &= N, \end{aligned}\right\} \tag{1}$$

where X and Y are the hydrodynamic forces and N the hydrodynamic torque. These forces and torques are complicated functions of the motion. If they are linearized along a straight line motion the following equations are obtained.

State Equations

The natural state variables are the sway velocity v, the turning rate r, and the heading ψ. If v and r are solved from (1) the following equations are obtained.

$$\frac{d}{dt}\begin{bmatrix} v \\ r \\ \psi \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} n \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix}\delta. \tag{2}$$

If normalized coordinates are introduced, where the length unit is the length of the ship and the time unit the time it takes to travel a ships length, the parameters of the state equations are surprisingly similar for many different ships. See Table 1.

The Nomoto Model

The transfer function from rudder to heading is given by

$$G(s) = \frac{K\,(1+sT_3)}{s\,(1+sT_1)\,(1+sT_2)}. \tag{3}$$

The parameters K, T_1, T_2 and T_3 may change considerably although the parameters of the state model do not change much. See Table 1. In many cases, however, one pole of the model is close to its zero and the model can be simplified to

$$G(s) \approx \frac{k}{s\,(s+a)}. \tag{4}$$

This model is called the Nomoto model. It has the following

Ship	Cargo	Cargo	Tanker	Tanker		Tanker	
Length	160	161	305	322		350	
Breadth	22.9	23.2	47.2	54.6		60.0	
Draught	9.1	6.9	18.5	21.7	12.2	22.3	9.0
Draught	9.1	8.1	18.5	21.7	14.9	22.3	12.0
Displ.	23.4	16.6	220	312	189	389	172
Speed	15.2	15.0	16.0	16.0	17.0	15.8	17.2
Prop RPM	74.4	69.0	80.0	100.0	98.4	87.6	87.6
a11	-0.895	-0.770	-0.597	-0.298	-0.428	-0.454	-0.431
a12	-0.286	-0.335	-0.372	-0.279	-0.359	-0.433	-0.448
a21	-4.367	-3.394	-3.651	-4.370	-2.959	-4.005	-1.976
a22	-0.918	-1.627	-0.792	-0.773	-1.011	-0.807	-1.145
b1	0.108	0.170	0.103	0.116	0.150	0.097	0.144
b2	-0.918	-1.627	-0.792	-0.773	-1.011	-0.807	-1.145
K	-1.092	-3.855	3.511	1.008	2.660	0.831	5.881
T1	2.743	5.660	-10.59	-3.091	-6.932	-2.882	-16.91
T2	0.308	0.372	0.390	0.443	0.438	0.382	0.447
T3	0.710	0.889	0.933	1.048	1.153	1.069	1.472
a	0.427	0.194	-0.090	-0.271	-0.131	-0.280	-0.056

<u>Table 1</u> - Parameters of statemodels for different ships. The parameters are given in normalized units. The Cargo ship 1 is a series 60 ship with a block coefficient 0.70. Cargo ship 2 is of the Mariner Class.

state representation.

$$\frac{d}{dt}\begin{bmatrix} r \\ \psi \end{bmatrix} = \begin{bmatrix} -a & 0 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} r \\ \psi \end{bmatrix} + \begin{bmatrix} k \\ 0 \end{bmatrix}\delta. \tag{5}$$

The parameter k of the Nomoto model can approximatively be expressed as follows.

$$k = c\left[\frac{V}{L}\right]^2 \frac{A_R L}{\nabla} \tag{6}$$

where L is the length of the ship, ∇ is the displacement , V the ship speed, A_R is the rudder area and c is a parameter whose value is approximatively 0.5. The parameter a will depend on trim, speed and loading. Its sign may change with the operating conditions. Disregarding the speed variations the parameter k does not change much with the operating conditions. The parameter a may however change considerably with the operating conditions. Typical ranges for a tanker under different operating conditions are given in Table 2.

Operating conditions	a	k
1	0.75	0.37
2	0.26	0.38
3	0.04	0.18
4	-0.11	0.14

Table 2 - Parameters a and k for a tanker under different operating conditions. The parameters are given in normalized units.

3. MODELS OF DISTURBANCES

Wind

The influence of the wind can be described by additional forces and torques. For tankers which are large the net effect is well described as the sum of a constant component and a white noise stochastic processes. This is possible because the ships length (300 m) is typically much larger than the turbulence scale. When winds are taken into account the Nomoto model is changed to

$$\frac{d}{dt}\begin{bmatrix} r \\ \psi \end{bmatrix} = \begin{bmatrix} -a & 0 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} r \\ \psi \end{bmatrix} + \begin{bmatrix} k \\ 0 \end{bmatrix}\delta + \begin{bmatrix} v \\ 0 \end{bmatrix} \tag{7}$$

where v = unknown constant + white noise.

The magnitude of the disturbances depends on the sea conditions. The forces are in general quadratic functions of the wind speed. At 10 m/s the wind torque could typically correspond to a velocity of 0.05 deg/s for a tanker.

Waves

The simplest wave model is a periodic force in the equations of motion. In the Nomoto model the waves can be modeled as a disturbance v in (5) where

$$v = v_o \sin \omega t.$$

The amplitude v_o depends on the sea conditions. The frequency of the disturbance will depend on the angle between the heading and the wave front. The most severe case occurs when the waves are coming from behind the ship. The wave frequency as seen from the ship could then be well inside the bandwidth of the servoloop. Typical values for sea state 5 are

$$v_o = 0.2^o s.$$

The frequency can be anywhere between 1-2 rad/s.

Measurements Errors

The heading is normally measured by a gyroscope. The gyro has a finite resolution. Typical values between 0.01 and 0.1 degrees. The gyro can also be disturbed by the ships motion. This contribution to the measurement errors will increase with increasing sea state. The turning rate is measured by a rategyro. This gyro is subject to drift which could be of the order of 10^{-6} rad/s. Due to crosscoupling effects the rategyro may also pick up yawing and heaving motions.

Nonlinearities

The linear model is only valid for small turning rates ($r<0.01$ deg/s). For larger turning rates it is necessary to take nonlinear effects into account. The major nonlinearity comes from the so called cross flow drag, which give rise to a force proportional to $v|v|$. If this is taken into account the Nomoto model is changed to

$$\frac{d^2\psi}{dt^2} + f\left(\frac{d\psi}{dt}\right) = k\,\delta. \tag{8}$$

The function f has the form

$$f(x) = a\,x + b\,x|x|.$$

See Fig. 2. Case B shown in Fig. 2 correspond to an unstable ship. If the rudder is kept at the midship position, there are three equilibrium values for the turning rate. The value $r = 0$ correspond to a straight line motion. This motion is unstable. The other equilibria correspond to the motions when the ship goes in circles turning starboard or port.

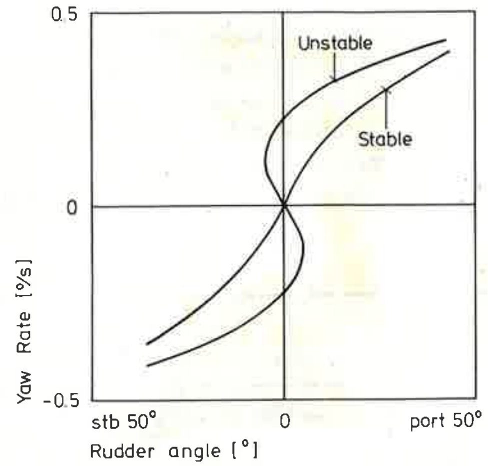

Fig. 2 Steady state yaw rate as a function of the rudder angle.

4. FORMULATION OF CONTROL PROBLEMS

Two simplified control problems are formulated. The first is a stabilization problem the second is an optimization problem.

Safe Operation

Find a feedback law for the Nomoto model (7) which gives satisfactory damping and response and moderate rudder motions. The feedback law could be of the form

$$\delta = K_{\psi}\left(\psi_{ref} - \psi\right) - k_r r.$$

The rudder angle may never exceed 40 deg. To avoid difficulties with amplification of disturbances and for high rudder motions the gains are limited by

$$|k_{\psi}| \le 10, \qquad |k_r| \le 100 \text{ s.} \tag{9}$$

The control problem can thus be formulated as to satisfy these constraints over all operating conditions e.g. those given in Table 2.

Economic Steering

When the ship is operating on the open seas the major problem is to steer the ship so that the steering losses are minimal. The increase of the drag due to yawing and steering can be determined from the x-component of the equations of motion. Several attempts have been made to obtain a simple loss function which is well suited to evaluate steering performance. The problem is not settled in the sense that there is universal agreement on the loss function. The following approximation is, however, often used

$$\frac{\Delta R}{R} = \beta \left[\bar{\psi}^2 + r\, \bar{\delta}^2 \right] \tag{10}$$

where $\bar{\psi}^2$ and $\bar{\delta}^2$ are the mean square deviation in heading and rudder angle. R is the drag and ΔR is the increased drag due to steering. The values of β and ρ depend on the ship. Typical values are $\beta=0.014$ and $\rho=0.08$ for a tanker and $\beta=0.007$ and $\rho=0.14$ for a cargo ship of the mariner class. Accepting the approxative loss function it seems resonable to base economic steering on minimazitation of criterion.

$$J = \lim_{T\to\infty} \frac{I}{T} \int \left[\psi^2(t) + \rho\, \delta^2(t) \right] dt. \tag{11}$$

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