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MARINE COURSE-CHANGING CONTROL USING THE POLE PLACEMENT METHOD WITH A POLYNOMIAL APPROACH

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ABSTRACT

This paper presents the design study of a controller for steering a ship which uses the pole placement method with a polynomial approach. The choice of the sampling interval is found to be very important. Simulation results demonstrate the good performance of such a controller. In particular, the controller followed the desired path in a course-changing maneuver with considerable accuracy. Moreover, this method is found to provide satisfactory results in spite of modelling errors.

KEYWORDS

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Ship autopilots, marine systems, control systems, ship control, ship model, course-changing control.

INTRODUCTION

Pole-placement design of a controller can be based on an input-output model or on a state-space. We have chosen the former model because it is one of the simplest methods to use since it is based on the manipulation of polynomials.

We apply this method to the control of course changing of a Mariner class cargo ship, using the first-order Nomoto model [1]. Simulation studies are shown for different design specifications. The results are compared with those obtained with a conventional PID autopilot. The response of the system with regard to modelling errors is also shown.

MATHEMATICAL MODEL OF THE SHIP

Figure 1 shows the block diagram of the steering system of the ship with a conventional PID autopilot. The reference signal ψ_r represents the desired heading angle, ψ_e the heading error, the rudder angle command δ_c is the signal that operate the steering gear and represents the rudder angle necessary to correct the deviation from the course, δ is the actual rudder angle, and ψ represents the heading of the ship.

The response of the ship ψ to a certain input δ may be given by different mathematical models [2]. If the relation is assumed to be linear, it can be written in the following way [1]:

$$\frac{\psi}{\delta}(\mathrm{s}) = \frac{K\,(1+sT_3)}{s\,(1+sT_1)\,(1+sT_2)} \tag{1}$$

where K, T_1, T_2 and T_3 are the parameters that represent the dynamic characteristics of the ship.

Equation (1) is usually approximated by the trasnfer function:

$$\frac{\psi}{\delta}(s) = \frac{K}{s(1+sT)} \tag{2}$$

with $T = T_1 + T_2 - T_3$

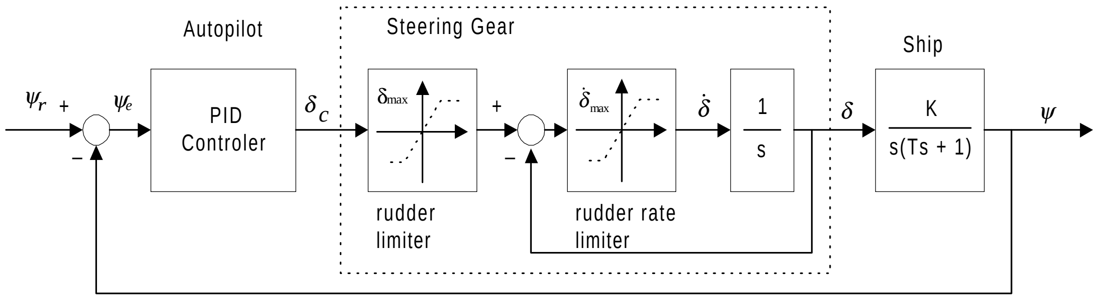

FIGURE 1 Block diagram of a conventional steering system

The parameters of the model are determined basically by the dimensions and shape of the vessel, and also depend on the operating conditions such as the speed, draft, load, trim and depth of water. In this paper, the plant to be controlled is considered to include everything involved in dynamic relationship between the rudder angle δ_c requested by the controller and the heading of the ship given by ψ.

STATEMENT OF THE PROBLEM

An autopilot must accomplish two objectives: course keeping and course changing. In the first case, the control objective is to keep the ship on course, regardless of disturbances caused by the wind, waves or currents; the course can be defined as $\psi(t)$ = constant.

In the second case, the course change should be effected as quickly as possible and without oscillations. It has been suggested [3] that the trajectory should be specified by means of a second-order reference model

$$\ddot{\psi}(t) + 2\varsigma\omega_n\dot{\psi}(t) + \omega_n^{\ 2}\psi(t) = \omega_n^{\ 2}\psi_r \tag{3}$$

ω_n is the natural frequency and ζ ($0{,}8 \le \zeta \le 1$) is the damping coefficient of the desired closed loop system.

STRUCTURE OF THE CONTROLLER

The closed loop system with pole-placement control [4] [5] can be represented by the block diagram in Figure 2, where the process is determined by the discrete transfer function $H(z) = \frac{B(z)}{A(z)}$, where A(z) and B(z) are polynomials without any common factors.

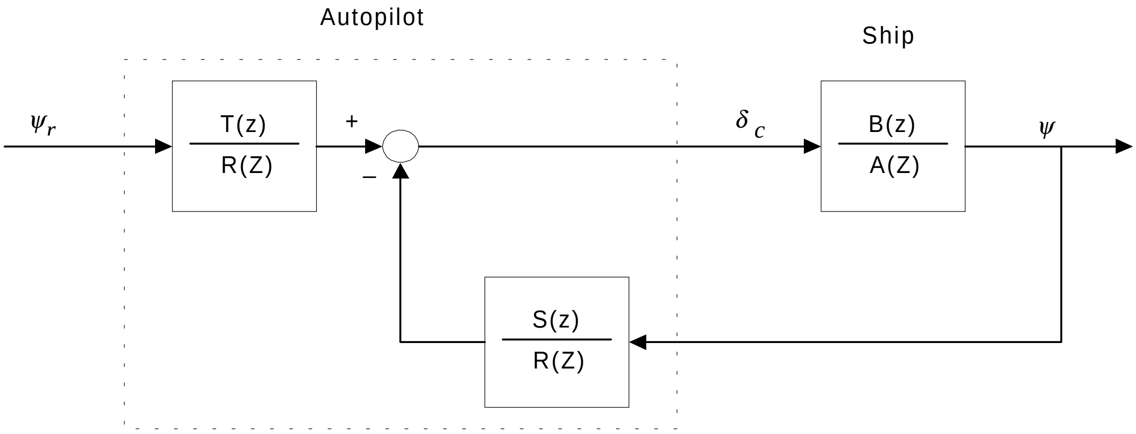

FIGURE 2 Block diagram of the pole-placement control system.

The control law consists of a feedforward term and an output feedback term:

$$R(q)u(k) = T(q)ref(k) - S(q)y(k) \tag{4}$$

where *R* (a monic polynomial), *S* and *T* are the polynomials to be calculated by means of this design [2].

The desired specifications of the servo are also expressed by a closed loop transfer function $H_m(z) = \frac{B_m(z)}{A_m(z)}$, where $A_m(z)$ and $B_m(z)$ have no common factors. It may be necessary to introduce stable cancellations into the model: $H_m(z) = \frac{B_m(z)A_0(z)}{A_m(z)A_0(z)}$, with $A_0(z)$ being the observer polynomial.

One of the characteristics of closed loop control systems is that they must satisfy the causality principle. In the case of a pole-placement controller, this involves some restrictions on the degree of the polynomials *R*, *S* and *T*:

deg$R \geq$ deg$T$ and deg$R \geq$ deg$S$.

There are two particular conditions for causality depending on the calculation time of the control signal:

1º) In the case where the calculation time is a small fraction of the sampling interval, then it is a causal controller if: deg$R$ = deg$T$ = deg$S$

2º) If the calculation time is approximately equal to the sampling interval, then it must hold that deg$R$ = 1 + deg$T$ = 1 + deg$S$, so that there will be a delay of one period in the controller.

DESIGN ALGORITHM

For the closed loop system defined above, the input-output relation will be satisfied if

$$\frac{BT}{AR + BS} = \frac{Bm}{Am} \tag{5}$$

Rational methods are used to choose the parameters that satisfy this equation and the control restrictions. Cancellation of poles and zeros must be performed because the order of a closed loop system is normally greater than the order of the model. Only stable poles and zeros can be cancelled out since otherwise the system would be unstable, even if *R, S* and *T* were found which verified the equation. Thus, the following steps must be carried out in the design process.

1) The stable zeros must be separated from the unstable ones in the process ($B(z)=B^{+}(z)B^{-}(z)$), where $B^{+}(z)$ is a monic polynomial.

2) Since the unstable zeros cannot be cancelled out, they must be included in the model, i.e. $B_m(z)=B^{-}(z)B_m^{'}(z)$.

3) So that the stable poles will be cancelled out, $R(z)=B^{+}(z)R^{'}(z)$ must be factored.

4) Since the observer polynomial has been cancelled (5), then:

$$T = B_m' A_0 \tag{6}$$

$$AR' + B^{-}S = A_0A_m \tag{7}$$

Equation (6) determines one of the polynomials (T) of the control law and equation (7) is the characteristic equation of the closed loop system.

5) The system must also fulfill some control restrictions concerning the causality of the control law. In order to obtain a causal solution, the following conditions must be satisfied:

$$\deg A_0 \geq 2\deg A - \deg A_m - \deg B^{+} - 1$$
$$\deg A_m - \deg B_m \geq \deg A - \deg B$$
$$\deg R' = \deg A_0 + \deg A_m - \deg A$$
$$\deg S = \deg A - 1$$

6) The polynomials *R'* and *S* can be deduced from the solution of the diophantine equation (7). A solution will exist if the greatest common divisor of the polynomials with real coefficients *A* and B^{-} divides A_0A_m.

SIMULATIONS

Now we will describe an autopilot to control the course of a ship, designed by using the methodology proposed.

For the simulation we chose the mathematical model of a Mariner class cargo ship whose main characteristics [6] are the following:

Length overall	171,80	m.
Length between perpendiculars........	160,93	m.
Maximum beam	23,17	m.
Design draft......................................	8,23	m.
Design displacement	18541	m^3.
Design speed	15	knots.

The following values [7] were used as parameters of the model:

$K = -0{,}185\ s^{-1}$, $T_1 = 118$ s, $T_2 = 7{,}8$ s y $T_3 = 18{,}5$ s

The simulation was performed using the SIMULINK *Matlab Toolbox.*

To apply the proposed design methodology, we defined the desired behavior for the course changing maneuver according to the trajectory defined in (3). A damping coefficient of ζ = 0.9 and a natural frequency of ω_n=0.01 rad/s were chosen as specifications in the time domain. On the basis of these specifications, the rise time t_r is determined and the sampling interval T_s is chosen, which should be between $t_r/4$ and $t_r/10$ [4]. This latter choice proves to be crucial in this design method. Figure 3 shows the desired result of a 10º course change together with the results of the course changing simulation for the four different adjustments of the controller indicated in Table 1.

In all cases a damping coefficient of ζ = 0.9 was used and it was found that a good response was obtained with t_r=500 s and T_s = 50 s.

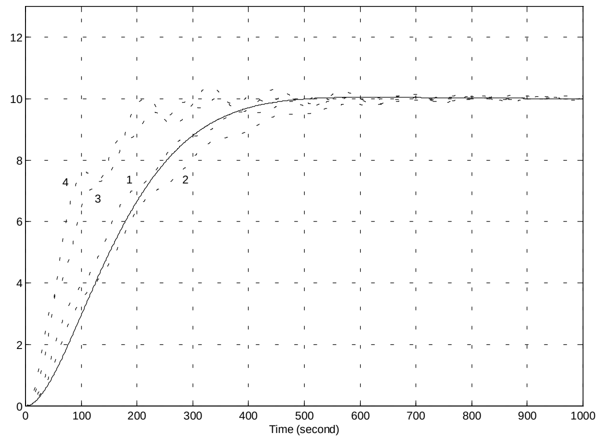

FIGURE 3: Desired course (solid), t_r=500, T_s=50 (dotted 1), t_r=600, T_s=60 (dotted 2), t_r=300,T_s=60 (dotted 3) , t_r=300, T_s=30 (dotted 4)

	t_r=500 s T_s = 50 s	t_r=600 s T_s = 60 s	t_r=300 s T_s = 30 s	t_r=300 s T_s = 60 s
R(z)	z+0.8563	z+0.8303	z+0.8303	z+0.911
S(z)	-0.258z+0.1606	-0.163z+0.0932	-0.3515z+0.1783	-0.859z+0.6025
T(z)	-0.0982z	-0.06986z	-0.17319z	-0.2565z

TABLE 1: Polynomials of the controller used in the pole-placement design method.

Figure 4 compares the course changing of a ship with a conventional controller to one with a pole-placement controller.

The conventional controller was a PID controller modified by adding one low-pass filter $(1 + T_L s)^{-1}$ to reduce the high frequency rudder demands and another $(1 + T_L s)^{-1}$ to attenuate the derivative action. The expression for the controller is [8]

$$G_R(s) = \frac{K_R(1+T_{PH}s)(1+K_{CR}T_{CR}s)}{T_{PH}(1+T_{CR}s)(1+T_L s)s} \qquad (8)$$

The controller is adjusted with the following values:

$K_R = 0{,}1$ $K_{CR} = 5$ $T_{CR} = 5$ $T_{PH} = 750$ $T_L = 0{,}3$

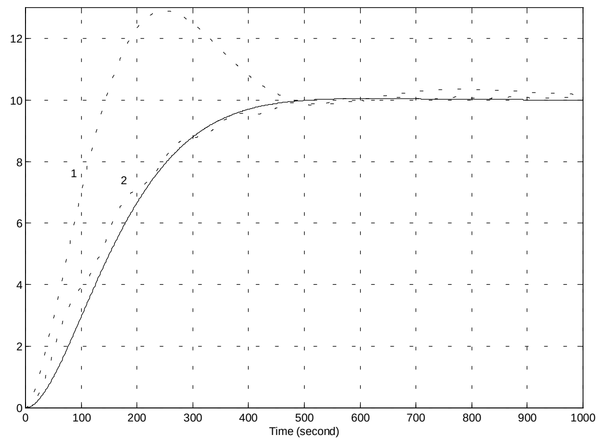

FIGURE 4: Desired course (solid), PID Control (dotted 1), pole-placement (dotted 2)

Figure 5 shows the behavior of the system in the presence of significant variations (±25%) in the modelling parameters. It can be seen that the desired course is still followed quite satisfactorily.

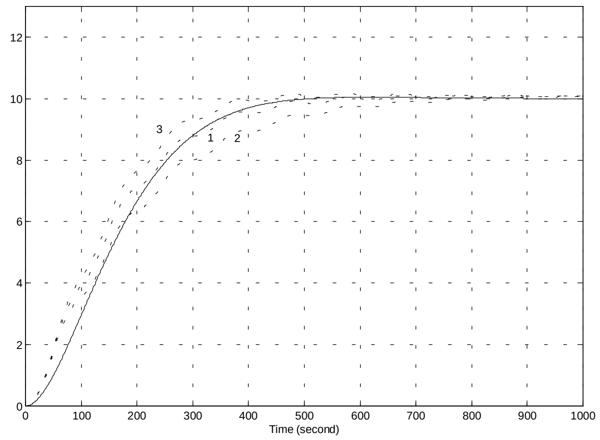

FIGURE 5: Desired course (solid), K = -0,185, T=107,3 (dotted 1),
K = -0,1387, T=80,475 (dotted 2), K = -0,23125, T=134,125 (dotted 3)

CONCLUSIONS

This work has presented a pole-placement method for designing an autopilot for a Mariner class ship. Simulation results have shown the performance of this controller to be quite good. The desired course is followed with considerable accuracy in a course-changing maneuver. Moreover, the behavior of the system remains satisfactory even when significant variations are introduced into the modelling parameters: the desired course is still maintained quite well. It was found that with this design method the rise time t_r and the sampling interval T_s. must be chosen with care.

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