TECHNICAL NOTE

DETERMINING ROBUST PARAMETERS IN STABILIZING SET OF BACKSTEPPING BASED NONLINEAR CONTROLLER FOR SHIP COURSE KEEPING

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SUMMARY

In order to solve the problem that backstepping method cannot effectively guarantee the robust performance of the closed-loop system, a novel method of determining parameter is developed in this note. Based on the ship manoeuvring empirical knowledge and the closed-loop shaping theory, the derived parameters belong to a reduced robust group in the original stabilizing set. The uniformly asymptotic stability is achieved theoretically. The training vessel "Yulong" and the tanker "Daqing232" are selected as the plants in the simulation experiment. And the simulation results are presented to demonstrate the effectiveness of the proposed algorithm.

1. INTRODUCTION

Nonlinear control scheme is frequently encountered in the control system design. The backstepping is a recursive design methodology developed in the recent two decades, and it can offer a choice of design tools for accommodation of uncertain nonlinearities and avoid the wasteful cancellations [1].

In the recent years, the backstepping method has been developed with the novel properties and applied to the ship course keeping task. An adaptive law was combined with a control design including a filtered backstepping controller and RBF neural network approximator [2], which could guarantee the ultimately uniformly boundedness for ship steering closed-loop system. Taking advantages of great robust performances of the sliding mode technique, the problem of "explosion of complexity" is effectively solved and the simple backstepping control law is developed for the ship autopilot [3]. The reference [4] discussed the problem of designing a proper and efficient adaptive course-keeping control system for a seagoing ship based on the adaptive backstepping method. Tracking control of surface vessels via fault-tolerant adaptive backstepping interval type-2 fuzzy control was discussed in the reference [5]. Combining the dynamic surface control and Nussbaum gain function with backstepping method, an adaptive nonlinear control strategy was proposed for the nonlinear course keeping control problem of ships with parameter uncertainties and completely unknown control direction [6]. In [7], An adaptive algorithm for stabilizing of ship motion on a nonlinear path was designed on the basis of a nonlinear ship motion model with the use of the backstepping method. From the simulation result of a river boat unsteady on its course, the control performance may be randomly deteriorated when the coefficients of the nonlinear model change. That is to say, the robustness of the developed algorithm is not guaranteed. To execute the straight-line tracking control task, the sliding mode-based impact time and angle guidance law was incorporated in [8]. And the basic robust control law was still designed using the backstepping method.
In the above backstepping related research work, the construction of both feedback control laws and associated Lyapunov functions is systematic. Some properties of global or regional stability or tracking are built into the closed-loop system in a number of steps. However, this method is only suitable for the standard nonlinear plant with the strict-feedback or pure-feedback form, and the robustness of the derived closed-loop system cannot be guaranteed in the quantitative aspect [9]. Motivated by the afore-mentioned observation, a novel robust control scheme is developed based on the backstepping method and CGSA (closed-loop shaping algorithm) in this note. By the virtue of the algorithm, the parameters for the Lyapunov function and stabilizing control law are more easily selected to guarantee the robustness. Furthermore, the closed-loop system for ship course keeping is designed using the proposed algorithm and the obtained robustness is proved theoretically. Simulation results have illustrated the effectiveness and robustness of the corresponding scheme.

2. DESIGN OF BACKSTEPPING BASED ROBUST CONTROL

In this section, the mathematical model for ship course keeping is found to be of the form.

$$\begin{aligned} &\dot{\psi}=r \\ &\dot{r}=-\frac{K}{T}\left(\alpha r+\beta r^{3}\right)+\frac{K}{T}\delta \end{aligned} \tag{1}$$

where ψ, r, δ are the heading angle, the heading rate, and the rudder angle for ships respectively. K, T are maneuverability indices of ships. It is noted that, $\alpha r+\beta r^3$ denotes the nonlinear relationship between δ and r, which can be identified by the well known experiment "spiral test" [10]. The objective of this note is to develop the nonlinear robust control law to drive the course of the vessel ψ, which follows the desired course reference angle ψ_r.

To facilitate the description, the result is first stated as follows, and then the prove details are presented.

Theorem 1: Considering the ship course keeping system (1), the proposed algorithm (2), developed using the backstepping method, is capable of guaranteeing the uniformly asymptotic stability and robustness of the closed-loop system by selecting properly $k_1 = 0.03,\ k_2 = T/(3K) - k_1$, K, T are the maneuverability indices).

$$u = \alpha r + \beta r^3 + \frac{T}{K}[(1 + k_1 k_2)e_1 + (k_1 + k_2)\dot{e}_1] \quad (2)$$

with $e_1 = \psi_r - \psi$ being the course deviation.

Proof: Set $x_1 = \psi$, $x_2 = \dot{x}_1 = r = \dot{\psi}$, and $e_1 = \psi_r \text{-} \psi$, then one can get the transformed model (3).

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x_2) + bu \\ y &= x_1 \end{aligned} \quad (3)$$

where the system output $y \in R$, $f(x_2) = -\frac{K}{T}H(r)$, $H(r) = \alpha r + \beta r^3$, $b = K/T$, $u = \delta$.

Step 1. Defining the first error variable $z_1 = x_1 - \psi_r$, $z_2 = x_2 - \phi(z_1)$, then we can get (4).

$$\dot{z}_1 = \dot{x}_1 - \dot{\psi}_r = x_2 - \dot{\psi}_r = z_2 + \phi(z_1) - \dot{\psi}_r \quad (4)$$

We choose an intermediate control function $\phi(z_1)$ for z_2 in the subsystem (4) as follows (5).

$$\phi(z_1) = \dot{\psi}_r - k_1 z_1 \quad (5)$$

where k_1 is a positive design constant. Submitting (5) into (4) to get $\dot{z}_1 = -k_1 z_1 + z_2$. Thus the first Lyapunov function candidate is constructed.

$$V_1 = \frac{1}{2} z_1{}^2 \quad (6)$$

$$\dot{V}_1 = -k_1 z_1^2 + z_1 z_2 \quad (7)$$

Step 2. A similar procedure is employed recursively for step 2. From (5), it is obtained

$$\dot{z}_2 = \dot{x}_2 - \dot{\phi}(z_1) = f(x_2) + bu - \dot{\phi}(z_1) \quad (8)$$

Furthermore, the following Lyapunov function is constructed.

$$V_2 = V_1 + \frac{1}{2} z_2{}^2 \quad (9)$$

$$\dot{V}_2 = -k_1 z_1^2 + z_2[z_1 + f(x_2) + bu - \dot{\phi}(z_1)] \quad (10)$$

We choose the actual control function (11) to guarantee $\dot{V}_2 \le 0$, k_2 is a positive design constant.

$$u = \frac{1}{b}\left(\dot{\phi}(z_1) - z_1 - f(x_2) - k_2 z_2\right) \quad (11)$$

Substituting (11) into (10), one can get

$$\dot{V}_2 = -k_1 z_1^2 - k_2 z_2^2 < 0,\ \ \forall z_1 \ne 0, z_2 \ne 0 \quad (12)$$

According to the Lyapunov theorem, the control law can stabilize the course keeping system effectively and all state variables in the closed-loop system are uniformly asymptotic stable with equilibrium $x_1 = \psi_r,\ \ x_2 = \dot{\psi}_r$.

Based on the above design, (14) is derived by substituting (13) into (11).

$$\dot{\phi}(z_1) = \ddot{\psi}_r - k_1 \dot{z}_1 \quad (13)$$

$$\begin{aligned} u = \frac{T}{K}(\frac{K}{T}H(x_2) - (1 + k_1 k_2)(x_1 - \psi_r) - \\ (k_1 + k_2)(x_2 - \dot{\psi}_r) + \ddot{\psi}_r) \end{aligned} \quad (14)$$

Selecting ψ_r as the common step function, (14) is further transformed into (15).

$$\begin{aligned} u &= H(x_2) + \frac{T}{K}[(1 + k_1 k_2)e_1 + (k_1 + k_2)\dot{e}_1] \\ &= H(x_2) + \frac{T}{K}v \end{aligned} \quad (15)$$

Comparing (15) with the mathematical model (1), one can find that, the essence of the backstepping method is to compensate the system nonlinearity and to stabilize the residual terms with a linear control law v , e.g. the PD(proportion-derivative) controller in (15).

In the proposed algorithm, one sets

$$\begin{aligned} k_p &= 1 + k_1 k_2 = 1 + k_1 T/(3K) - k_1^2 = 1/(3K) + \rho \\ k_d &= k_1 + k_2 = T/(3K) \end{aligned} \quad (16)$$

with $\rho = k_1 T/(3K) - k_1^2 + 1 - 1/(3K)$.

Substituting (16) into (15), (17) is derived.

$$u = H(x_2) + \frac{T}{K}[(1/(3\text{K}) + \rho)e_1 + T/(3K)\dot{e}_1] \\ = H(x_2) + \frac{T}{K}v \quad (17)$$

CGSA is a simplified H_∞ mixed sensitivity algorithm by directly shaping the singular value curves of the sensitivity function $S(s)$ and the complementary sensitivity function $T(s)$, and there exists the correlativity $T(s) = I - S(s)$. For a typical stable plant, the high-frequency asymptote slop of $T(s)$ is usually suggested to be -20dB/dec, -40dB/dec, -60dB/dec, which are corresponding to the first-order, second-order and the third-order CGSA. In this note, the linear control law (18) with PD form is obtained by virtue of the first-order CGSA [9, 11]. For the linear Nomoto plant $G(s)=\psi/\delta=K/[s(Ts+1)]$ which equals to the plant omitting the nonlinear items in (1), the linear robust controller is as follows.

$$v = \frac{1}{GT_1 s}e_1 = \frac{Ts+1}{KT_1}e_1 = (\frac{1}{KT_1} + \frac{T}{KT_1}s)e_1 \\ = \frac{1}{KT_1}e_1 + \frac{T}{KT_1}\dot{e}_1 \quad (18)$$

where T_1 is the parameter to be adjusted and it can be chosen according the reciprocal of system bandwidth.

According to the empirical conclusion of designing the classical PD control [9], one positive constant ρ ($\rho < 10$) added in the proportional term of (18) would improve the performance for ship course keeping control, i.e. Eq.(19). Actually, for the classical PD controller, it can improve the transient performance (e.g. the speedability) of the system response to increase the proportional coefficient. And the differential term (increasing the differential coefficient reasonably) could improve the stability of the closed-loop system.

$$v = (\frac{1}{KT_1} + \rho)e_1 + \frac{T}{KT_1}\dot{e}_1 \quad (19)$$

Comparing (17) with (19), the linear part in (17) equals to the concise robust control (19) with $T_1 = 3$, to attenuate the high frequency wave interference.

Considering the ship maneuvering dynamics, $k_1 + k_2$ in (16) is a larger value (in general $k_1 + k_2 \geq 100$). In addition, $\rho < 10$. One can get $k_1 k_2 < k_1 + k_2, k_1 k_2 \leq 10$ from (16), i.e., $k_1 < 0.1$ or $k_2 < 0.1$. In this note, k_1 is selected as 0.03 for concerning the dynamics of very large carriers. Thus, $k_2 = T/(3K) - k_1$. According to the closed-loop gain shaping algorithm [11], the proposed control law (2), could obtain the uniformly asymptotic stability and robust performance of the closed-loop system simultaneously.

3. ANALYSIS OF SIMULATION RESULTS

Taking the "Yulong" training ship of Dalian maritime university as an example, whose particulars are: length between perpendiculars L=126 m, beam B=20.8 m, displacement ∇ =14278.1 m^3, draught D=8.0 m, block coefficient C_b =0.681, distance from center of mass to the origin of x axis x_c = -3.38m, ship speed V =15 kn, rudder area A_δ=18.8m^2. The maneuverability indices of the nonlinear Nomoto model for ships can be calculated from the above parameters [10]: K =0.48 s^{-1}, T =216.58 s, $\alpha = 9.16$, $\beta = 10\,814.30$. The nonlinear Nomoto model with a rudder servo system is used when the simulation experiment is carried out. In the simulation, the parameters in the control law (2) are as follows: $k_1 = 0.03$, $k_2 = T/(3K) - k_1$ =150.37, i.e. $k_p = 5.51, k_d = 150.4$. The steering engine of the rudder servo system is modeled as a system with single hydraulic circuit analog control variable, the maximum rudder rate is ±5°/s and the saturation rudder angle is ±35°.

When the ship is navigating on the sea, the sway motion and heading deviation are caused mainly by wind and wave disturbances, therefore the effects of wind and wave cannot be neglected in the simulation. For the wind disturbance, it is divided into the average wind and impulse wind. The impulse wind is implemented using white noise while the average wind is related with the leeway and is expressed as an equivalent rudder angle δ_{wind}. According to the references [12-14], δ_{wind} can be computed by an empirical formula as shown in Eq. (20).

$$\delta_{\text{wind}} = K^0 (\frac{V_\text{R}}{V})^2 \sin\gamma \quad (20)$$

where K^0 is the coefficient of leeway, V_R the relative wind speed to the ship, V the ship speed, γ the wind angle on the bow. When the wind scale is Beaufort No.6 and the wind angle on the bow is -30°, the equivalent rudder angle of wind can be calculated out as $\delta_{\text{wind}} = 3°$.

For the wave disturbance in the simulation, a simplified model is used which is a second-order oscillating system driven by a white noise [9], and the transfer function of the wave model under the wind scale of Beaufort No.6 is:

$$h(s) = \frac{0.4198s}{s^2 + 0.3638s + 0.3675} \quad (21)$$

The white noise with noise power 0.0001 is simulated by sample time of 0.5 s; it is the same as that in the simulation of random wind.

The simulation diagram implemented in Simulink is shown in Figure 1, the setting course is 40º, and the wind scale is Beaufort No.6. Simulation results are presented in Figure 2 and Figure 3, including the nominal model case and the perturbed one. In Figure 2(a), the ship heading angle is effectively stabilized with the rise time 70s, no overshoot and the static errors. Figure 2(b) presents the signal of the rudder angle. For the perturbed model case (considering the effect of the steering servo engine and Beaufort No.6 wind scale, it is indicated using the dash line in the Figure 2), the performance is not worse except the pronounced surging amplitude $\pm 2°$.

In order to verify the feasibility of Theorem 1, another tanker "Daqing232" is incorporated as the plant with length between perpendiculars L=152 m, displacement ∇ =20246 m^3, ship speed V =15 kn, K=0.16 s^{-1}, T=104.55 s, $\alpha=14.22$, $\beta=22444.52$. According to Theorem 1, $k_p=7.51, k_d=217.8$, and the analysis conclusion for Figure 3 is identical to that of Figure 2.

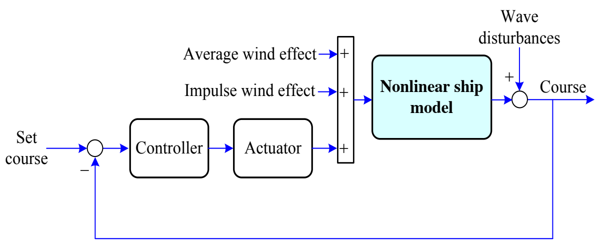

Figure 1. Simulation diagram of Simulink.

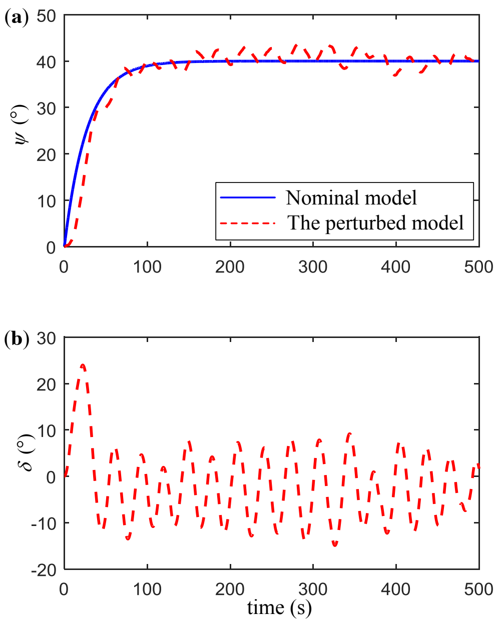

Figure 2. Simulation results of "Yulong" training vessel: (a) the ship heading angle and (b) the rudder angle.

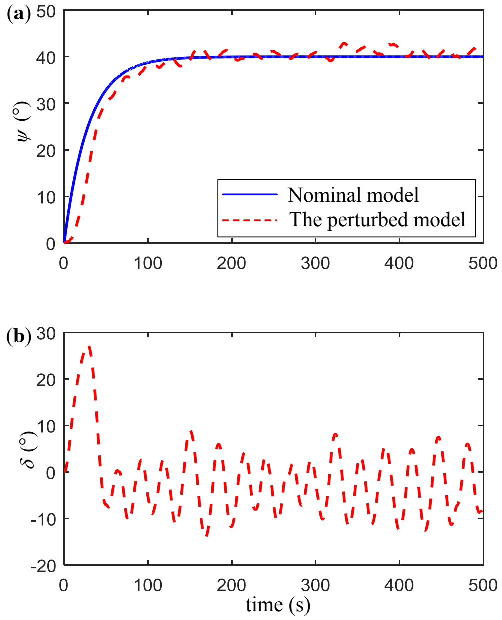

Figure 3. Simulation results of "Daqing232" tanker: (a) the ship heading angle and (b) the rudder angle.

4. CONCLUSIONS

Based on the empirical knowledge around ship maneuvering and control design, a novel method for determining the control parameters is developed by fusion of the backstepping method and CGSA. With the proposed scheme, a group of definite robust parameters could be determined from its original stabilizing set with more practical applicability. The uniformly asymptotic stability is proved theoretically and simulation results have illustrated the effectiveness and robustness of the corresponding algorithm.

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