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Disturbance rejection control solution for ship steering system with uncertain time delay

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ABSTRACT

The control problem for a ship steering system with uncertain time delays is discussed in this paper. The system uncertainties, including parameters and delay variations as well as unmodeled dynamics, are taken as "internal disturbances", while ocean movements are taken as "external disturbances". The combination of the two is considered as the "total disturbances" of the system. With the aid of a modified Smith predictor, an extended state observer (ESO) is constructed to estimate the total disturbances. By compensating its effects in a closed loop, the system is reduced to a set of cascaded integrators, which can be easily handled. The advantages of the proposed approach lie in two aspects: (1) it does not need an accurate model of the system; (2) it is robust against delay variations. The simulation results validate the strong disturbance rejection capability of the proposed method.

1. Introduction

In ship motion control, time delays are common and have different sources. The dominant kind of delay, known as input delay, is produced in actuators, such as rudders and propellers. The input time delay is generally defined as the estimated time lag between the sample event and a change in the actuators (Åström and Källström, 1976), that is the response time to the sample event. Another obvious kind of time delay is that between the sensors and the activation of the control mechanism (Chung et al., 1990), which is sometimes known as network-induced delay. Whatever the reasons for the time delays are, the aftereffect is similar and profoundly significant. The most notable effect of the time delay is the reduced stability of the system because of the extra phase lags, which create extra issues for control designers.

Since the Smith "posicast control" (Smith, 1957) and predictor (Smith, 1959) in the late 1950s, the literature has focused on the control of delay systems. Some existing solutions were established based on certain assumptions. For example, supposing that the delay is constant and known, related works include finite-dimensional approximations (Mäkilä and Partington, 1999a,b; Al-Amer and Al-Sunni, 2000), adaptive identification techniques (Foda and Mahmoud, 1998; Blanchini and Ryan, 1999; Verriest, 1999), observers-based methods (Sename, 2001) and improved Smith predictors-based approaches (Normey-Rico and Camacho, 2008). Sira-Ramírez et al. (2010) proposed a Generalized Proportional Integral (GPI) observer-based Smith predictor control scheme. Other attempts for delay systems, such as sliding mode control (Choi and Hedrick, 1998; Gouaisbaut et al., 1999), may either induce oscillations around the sliding surface or not allow a satisfactory disturbance rejection (Richard, 2003). These proposed solutions tackled the problem from two angles. One was attempting to identify the delay induced effect, while the other was suppressing the system uncertainties by infinite gains.

However, infinite gains demand high power levels from the actuators as well as high cost, which is unacceptable in engineering practice. Moreover, the assumption of constant and known delay is sometimes unrealistic. We must face the real problem that the time delay information often changes and is not easy to be modeled accurately, which makes the delay information too complex to be identified. Given the significant uncertainties in both the system model and delay knowledge, it seems that the input–output signals are the only information which can be directly obtained in the system.

Recently, it was reported in the Wall Street Journal (2013) that Texas Instruments had released a new InstaSPIN motion control technology , with a control solution named Active Disturbance Rejection Control (ADRC). The ADRC can estimate and compensate, in real-time (SPRUHJ0, 2013), disturbances in the system from input–output information only, which offers a possible new solution for systems with delay. The ADRC was first proposed in a nonlinear form by Han (2008, 2009) and then simplified to a linear form for industrial purposes by Gao (2003). A large number of control problems, such as servo, temperature, web tension, aerospace and aeronautics, high energy physics, knee

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rehabilitation manipulator (Madonski et al., 2014a), water management system (Madonski et al., 2014b), have proved the effectiveness of ADRC (Qing and Zhiqiang, 2010). Recent theoretical analysis of ADRC can be found in Huang and Xue (2012), Zheng et al. (2012), Guo and Zhao (2011a,b, 2012a,b), Guo and Jin (2013), Guo and Zhao (2013), Nowicki et al. (2014). To some extent, ADRC is like the ideology developed by Fliess (1990) that forces a complex system to a so-called "normal form", which simplifies the control design.

In this paper, we propose a modified predictive ADRC for systems with time delay. This approach is believed to have the following advantages over the existing solutions: (1) it is less dependent on the mathematical model of the plant; (2) it is immune to a possible large delay variation without parameters retuning.

We take the example of a ship steering systems with large time delay to illustrate the applicability of the proposed method.

The rest of the paper is organized as follows. Section 2 formulates the problem of delayed ship steering system. The proposed solution is introduced in Section 3. Section 4 presents the conducted case study. Section 5 concludes the work.

2. Problem formulation

It is well known that the motion of a ship is characterized by large inertia, significant time delay, and nonlinearity. One should firstly assume some premises before establishing a mathematical model suitable for controller design.

Assuming that drift angle is very small and that the ship is operating at a constant speed in early stage, then the renowned NOMOTO model for heading control design can be obtained as in (Källström and Åström, 1981; Nomoto, 1957)

$$G(s)=\frac{\psi(s)}{\delta(s)}=\frac{K}{s(Ts+1)}e^{-\tau s} \tag{1}$$

where ψ is the heading angle and δ is the rudder angle. K and T are obtained from experimental data or by hydrodynamic calculation. The parameter K is called the turning ability index, while T is the turning lag index. The parameter τ represents the time delay which is not exactly known.

System (1) can be expressed in the time domain considering the external disturbance $w(t)$ as

$$\ddot{\psi}=\underbrace{-\frac{1}{T}\dot{\psi}+w(t)}_{d}+\frac{K}{T}\delta(t-\tau) \tag{2}$$

The problem here is driving the heading angle ψ to follow the reference angle ψ^* by controlling rudder angle δ to counteract the system total disturbance $d\triangleq-(1/T)\dot{\psi}+w(t)$.

If we make further assumptions that

A1: The system model accurately represents the real system.
A2: The delay is known.
A3: $w(t)$ represents the external disturbance accurately.

Then the problem may be easily tackled by calculating $\delta(t-\tau)=(T/K)(\ddot{\psi}+-(1/T)\dot{\psi}+w(t))$.

However, in real ship engineering, the foundations of the above proposed controller are questionable. To the best of our knowledge, $-(1/T)\dot{\psi}$ in Eq. (2) would be replaced by a nonlinear term for some static unstable ships. It cannot be modeled or approximated precisely due to the complexity of the system dynamics. These are the significant uncertainties of the system, together with the unknown time delay, the problem becomes even more complex to handle.

In this paper, we do not attempt to design a controller relying on an accurate mathematical model of the ship, instead we estimate and compensate the system uncertainties online based on the ADRC approach, which is the main contribution of this work.

3. Proposed ADRC-based solution

3.1. For system without delay

Firstly, we consider the system (2) without time delay, that is

$$\ddot{\psi}=-\frac{1}{T}\dot{\psi}+w(t)+\frac{K}{T}\delta \tag{3}$$

Let $x_1=\psi$, $x_2=\dot{\psi}$, the system (3) can be rewritten as

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=-\frac{1}{T}x_2+w(t)+\frac{K}{T}\delta\\ \psi=x_1\end{cases} \tag{4}$$

Note that if we let $d(x_2,w(t),t)=-(1/T)x_2+w(t)$, $b\approx K/T$, the system can be expressed in a more general form as

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=d(x_2,w(t),t)+b\delta\\ \psi=x_1\end{cases} \tag{5}$$

However b is usually not precisely known, so we take an estimation of b in the form of b_0, and denote term $d(\cdot,t)=d(x_2,w(t),t)+(b-b_0)\delta$ as time-varying total disturbances, including "internal disturbances" and "external disturbances", which unnecessarily needs to be expressively known. By treating $d(\cdot,t)$ as an extra state variable and assuming it as two times differentiable, $x_3=d(\cdot,t)$, and let $\dot{d}(\cdot,t)=g(t)$, $\ddot{d}(\cdot,t)=k(t)$ with $k(t)$ unknown,then model (5) can be rewritten as

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=x_3+b_0\delta\\ \dot{x}_3=x_4\\ \dot{x}_4=k(t)\\ \psi=x_1\end{cases} \tag{6}$$

which is always observable. Assuming that the total disturbances are completely unknown, a linear fourth order Extended State Observer (ESO) can be constructed, based on (6), to obtain the estimations of x_1, x_2, x_3 and x_4. The fourth order ESO is described as

$$\begin{cases}e=Z_1-\psi\\ \dot{Z}_1=Z_2-\beta_1 e\\ \dot{Z}_2=Z_3-\beta_2 e+b_0\delta\\ \dot{Z}_3=Z_4-\beta_3 e\\ \dot{Z}_4=-\beta_4 e\end{cases} \tag{7}$$

where e is the output estimation error, Z_1, Z_2, Z_3 and Z_4 are the observer outputs, and β_1,β_2,β_3 and β_4 are the observer gains. The roots of the observer can be placed at ω_o for the sake of convenient parameters tuning, that is

$$p_o(s)=s^4+\beta_1 s^3+\beta_2 s^2+\beta_3 s+\beta_4=(s+\omega_o)^4 \tag{8}$$

where ω_o is the bandwidth of the observer, and $\beta_1=4\omega_o$, $\beta_2=6\omega_o^2$, $\beta_3=4\omega_o^3$, $\beta_4=\omega_o^4$. For appropriate values of ω_o, Z_1 approaches ψ, Z_2 approaches $\dot{\psi}$, Z_3 approaches $d(\cdot,t)$, and Z_4 approaches $g(t)$.