SENSORLESS PROPELLER SPEED AND TORQUE ESTIMATION APPLIED TO REMOTELY OPERATED UNDERWATER VEHICLES PROPULSION SYSTEM

Leonardo Prudêncio, leonardop@cpdee.ufmg.br
Leonardo Antônio Borges Tôrres, torres@cpdee.ufmg.br
Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil

Abstract. *The main objective of the present work is to investigate the existence of unknown input state observer in the problem of sensorless speed and torque estimation of a DC motor driven propeller. Such problem is usually found in underwater vehicle propulsion systems, where the use of external speed and/or torque sensors can lead to greater system complexity and, at the same time, smaller system overall reliability. Therefore, in this case, the computation of speed and torque solely from motor electrical current and voltage measurements is very attractive. The approach followed is to investigate variations of the classical observer theory by considering the hydrodynamic torque as an unknown input. Although simultaneous exact state reconstruction and unknown input recovery cannot be guaranteed in a general context, it is possible to employ a simple and more specific technique to obtain promising results, if one considers the expected smooth, i.e. low frequency, dynamical evolution of the hydrodynamic torque, as it will be shown on this paper.*

Keywords: *Sensorless speed and torque estimation, propulsion system, underwater vehicles.*

1. INTRODUCTION

Unmanned Underwater Vehicles (UUVs) speed and position control systems are subject to an increased focus with respect to performance and reliability (Guibert et al., 2005; Fossen and Blanke, 2000). This is due to a growing number for scientific, commercial and military applications of UUVs to perform complex tasks (Whitcomb, 2000). In order to improve their precision, the thrust control systems should have high performance and reliability. The design of these controllers is not a trivial task and is limited by two problems (Bachmayer et al., 2000): 1) the vehicle's dynamics and 2) the dynamics of the bladed thrusters commonly used as actuators. This paper addresses the latter problem.

The block diagram depicted in Figure 1, shows a closed-loop position control system of a Remotely Operated underwater Vehicle (ROV). In this figure T_d is the desired thrust, v_m is the electric voltage motor, T denotes the actual propeller thrust and Ω is the feedback propeller angular speed. As shown in Figure 1, both ROV dynamical analysis and controllers design are improved when an accurate thruster model is used. The researches developed in (Kim and Chung, 2006; Bachmayer et al., 2000; Whitcomb and Yoerger, 1999; Healey et al., 1995; Yoerger et al., 1990) proposed some dynamic thruster models. In all these works, a specific instrumentation was utilized to parameters identification and model validation for each proposed model. This instrumentation is very expensive which limits the reproduction of any procedures reported in those works for mathematical thruster modeling. Another critical question is the measurement of some variables which influence the actual thrust, for example propeller angular speed and ambient flow velocity. The knowledge of these variables is very important to achieve a good thrust control performance. However, the feedback of these variables by using external sensors is expensive and the use of them can lead to greater system complexity and, at the same time, smaller system overall reliability. In this context, the motivation and the main objective of this paper, is to investigate the performance of the observer proposed in (Buja et al., 1995) to estimate the dynamical response of a thruster equipped with DC motor. As it will be shown, this observer based on motor electrical current and voltage measurements, can be used to estimate the propeller load torque, propeller angular speed and axial thrust developed by the thruster.

This paper is organized as follows: Section 2 models the DC drive system considered in this paper. Section 3 presents the observer proposed by Buja et al. (1995). Section 4 describes, briefly, a thruster model that will be used to investigate the observer performance. The simulation results are shown in Section 5. Section 6 concludes the paper.

2. SYSTEM MODEL

An electrical thruster equipped with separately excited DC motor can be modeled as:

$$\begin{aligned} v_m &= L_a \frac{di_a}{dt} + R_a i_a + K_f \Omega, \\ J_m \frac{d\Omega}{dt} &= K_t i_a - K_b \Omega - Q, \end{aligned} \tag{1}$$

where i_a and v_m is the motor electrical current and motor armature control voltage which is generated by a pulse width modulated device (PWM), commonly used in underwater vehicles propulsion system. The parameters L_a and R_a are armature inductance and resistance, K_f and K_t are the back emf and torque constants. J_m and K_b are the total moment

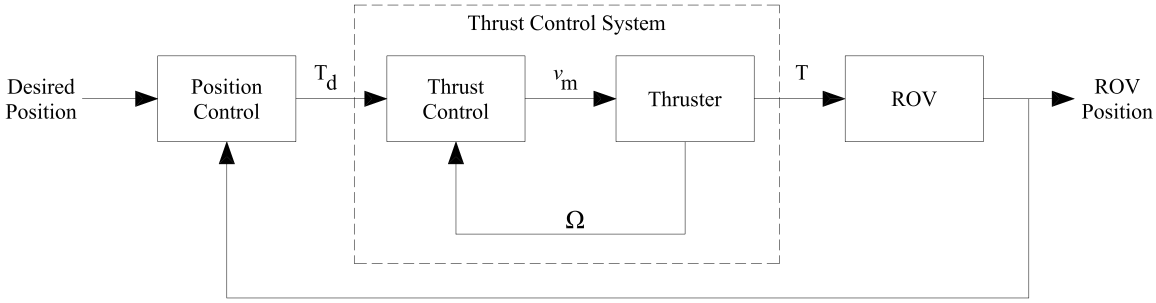

Figure 1. Position control block diagram

of inertia and viscous friction constant respectively and Q is the propeller load torque. This propulsion system is depicted in Figure 2 where T and U_a are the axial propeller thrust and axial flow velocity. Since in speed-sensorless operation, only current and voltage are measured (Bowes et al., 2004; Buja et al., 1995), equations (1) can be rewritten in the state form as:

$$\dot{\mathrm{x}} = \mathbf{A}\mathrm{x} + \mathbf{B}u + \mathbf{G}d \tag{2}$$

$$\mathrm{y} = \mathbf{C}\mathrm{x} \tag{3}$$

where:

$$u = v_m,\ d = Q,\ \mathrm{x} = \begin{bmatrix} i_a \\ \Omega \end{bmatrix},\ \mathbf{A} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_f}{L_a} \\ \frac{K_t}{J_m} & -\frac{K_b}{J_m} \end{bmatrix},\ \mathbf{B} = \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix},\ \mathbf{C} = \begin{bmatrix} 1 & 0 \end{bmatrix},\ \mathbf{G} = \begin{bmatrix} 0 \\ -\frac{1}{J_m} \end{bmatrix}. \tag{4}$$

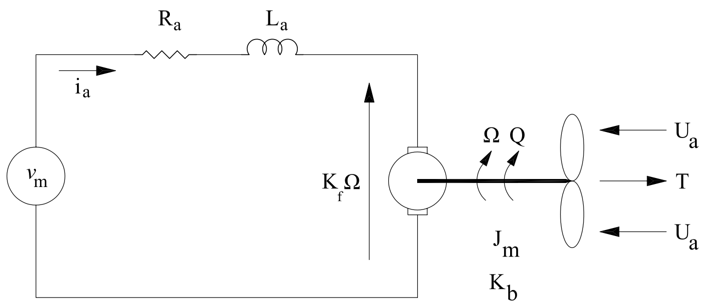

Figure 2. Marine thruster system driven by DC motor

This paper considers the dynamic equations (2) and (3) as linear time-invariant, and driven by both known input v_m and completely unknown input Q.

3. THRUSTER OBSERVER

In this section a thruster observer will be derived. The observer is able to deliver an accurate estimation of propeller angular speed and hydrodynamic load torque. In steady-state regime, the observer also estimate accurately the propeller axial thrust as it will be shown.

The observer is derived by an extension of the classical observer theory to a system with unknown inputs and i s based in (Buja et al., 1995). The estimation scheme is more attractive than the observers proposed in (Pivano et al., 2006a,b; Guibert et al., 2005) since only two easily measurements signals are necessary: armature motor electrical current and voltage. To a good observer performance, is considered by hypothesis hydrodynamic load torque dynamic evolution nearly constant with respect to the dynamics of the observer.

3.1 Propeller Load Torque and Angular Speed Observer

In the mathematical development to derive the observer, the propeller hydrodynamic torque Q is considered as an unknown input. As the pair $\mathbf{A}$ and $\mathbf{C}$ in equations (2) and (3) is observable, from the classical observer theory the state vector of the system, in the absence of the unknown input Q ($d = 0$), can be estimated by the following classical observer:

$$\dot{\hat{\mathrm{x}}} = \mathbf{A}\hat{\mathrm{x}} + \mathbf{B}u + \mathbf{GC}(\mathrm{x} - \hat{\mathrm{x}}), \tag{5}$$

where

$$\mathbf{G} = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}, \tag{6}$$

is the observer gain vector. However, applying this observer to estimate the estate vector $\mathtt{x}$, an estimation error is inevitable when $d = Q \neq 0$. The error dynamics is obtained by subtracting (2) from (5), in this case, resulting in:

$$\dot{e}_i = -\frac{(R_a + g_1 L_a)}{L_a} e_i - \frac{K_f}{L_a} e_\Omega, \tag{7}$$

$$\dot{e}_\Omega = \frac{(K_t - g_2 J_m)}{J_m} e_i - \frac{K_b}{J_m} e_\Omega - \frac{Q}{J_m}, \tag{8}$$

where e_i and e_Ω are electrical current and propeller angular speed errors respectively. For a low frequency hydrodynamic torque signal, the estimation errors tend to constant non-zero values. Considering that the current error is known as it is the difference between the measured current and the estimated one, an estimation of propeller load torque can be done by:

$$\tilde{Q} = \frac{K_f(K_t - g_2 J_m) + K_b(R_a + g_1 L_a)}{K_f} e_i. \tag{9}$$

Considering $\dot{e}_i \approx 0$ in (7), the estimation of propeller angular speed error is:

$$e_\Omega = -\frac{(R_a + g_1 L_a)}{K_f} e_i. \tag{10}$$

Therefore the actual propeller angular speed can be estimated by:

$$\tilde{\Omega} = \hat{\Omega} + e_\Omega. \tag{11}$$

In the equations above both ˆ and ˜ denote estimated vectors but the vectors with ˆ are obtained by using the classical observer, while a vector with ˜ is obtained by using an algorithm different from or added to the classical observer.

3.2 Thrust Observer

The static relation between thrust and propeller torque is nearly linear (Smogeli, 2006; Pivano et al., 2006a,b). In this case the propeller thrust can be computed as a static function of the propeller hydrodynamic torque estimation (Pivano et al., 2006a,b). The thruster observer is shown in Figure 3.

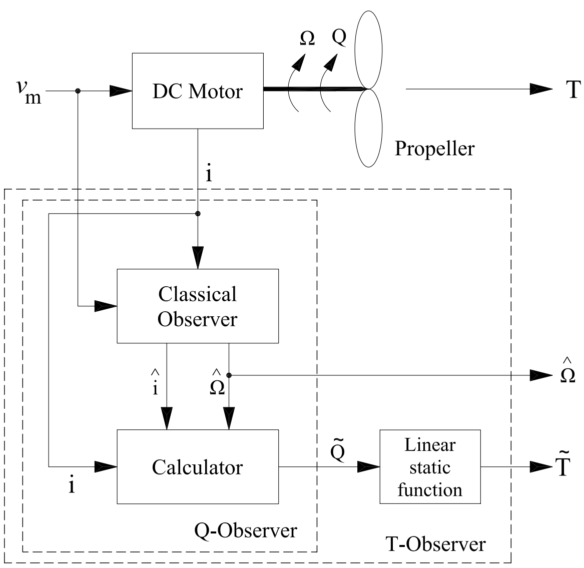

Figure 3. Thruster observer

4. THRUSTER MODEL

The two-state nonlinear thruster dynamic model proposed in (Healey et al., 1995) will be applied to investigate the thruster observer performance. This model, with propeller angular speed Ω and axial flow velocity U_a as state variables, is able to reproduce overshoots in thrust which are typically observed in experimental data. The control input is motor drive voltage v_m. The model has three parts: motor model, hydrodynamic model and propeller model which will be briefly described in this section.

4.1 Motor Model

The motor shaft dynamics can be written from (1) as:

$$\dot{\Omega} = -K_1\Omega + K_2 v_m - K_Q Q, \tag{12}$$

where

$$K_1 = \frac{1}{J_m}\left[\ \frac{K_t K_f}{R_a} + K_b\ \right], \quad K_2 = \frac{K_t}{J_m R_a}, \quad K_Q = \frac{1}{J_m}. \tag{13}$$

4.2 Hydrodynamic Model

To derive the hydrodynamic model, the conservation of linear momentum theorem was applied to a control volume of water around the propeller. Considering: 1) gravity and rotational flow as negligible effects; 2) incompressible flow and 3) inviscid flow, the authors proposed the following hydrodynamic model:

$$\dot{U}_a = -K_4 K_3^{-1} U_a |U_a| + K_3^{-1} T, \tag{14}$$

where

$$K_3 = \rho A_P L \gamma, \quad K_4 = \rho A_P \Delta\beta. \tag{15}$$

In the equation above, ρ is the water density, A_p is the disc area of the tunnel that shrouds the propeller, L denotes the length of the tunnel, γ is the added mass ratio and the parameter $\Delta\beta$ is called the differential steady momentum flux coefficient.

4.3 Propeller Model

The propeller represents the interface between motor dynamics and fluid dynamics (Bachmayer et al., 2000). The authors wrote the propeller axial thrust and load torque as a function of propeller blade lift force L and drag force D as:

$$T = L\cos(\theta) - D\sin(\theta), \tag{16}$$

$$Q = 0{,}7R[L\sin(\theta) + D\cos(\theta)], \tag{17}$$

where

$$\begin{aligned} L &= 0{,}5\rho V^2 A_P C_{Lmax}\sin(2\alpha), \\ D &= 0{,}5\rho V^2 A_P C_{Dmax}(1-\cos(2\alpha)), \\ \theta &= \arctan(U_a/0{,}7\Omega R), \\ \alpha &= p_p - \theta, \\ V^2 &= U_a^2 + (0{,}7\Omega R)^2. \end{aligned}$$

In the equation above, θ is the water incidence angle, α is the angle of attack, R denotes the propeller radius, p_p is the blade pitch angle and V is the total fluid velocity. The constants C_{Lmax} and C_{Dmax} are the maximum values of sinusoidal approximation of lift and drag coefficients.

5. SIMULATIONS RESULTS

The Thruster observer performance has been analyzed comparing the simulation data of the model proposed in (Healey et al., 1995) with the observer response. The thruster model parameters, utilized in the simulations, have been obtained from (Souza, 2003) and are given in Table 1. The observer matrix gain **G** is computed considering the observer dynamics at least two times faster than the DC motor dynamics. However, saturation and noise problems impose constraints on the matrix gain selection (Chen, 1998). In this paper, to compute the matrix gain **G**, the observer dynamics was considered two times faster than DC motor, resulting in the following:

$$\mathbf{G} = \begin{bmatrix} 3310.14 \\ -6781.27 \end{bmatrix}. \tag{18}$$

Table 1. Thruster model parameters

DC Motor	Hydrodynamic
$R_a = 1.7\Omega$	$C_{Dmax} = 1.25$
$L_a = 1.4 \times 10^{-3}H$	$C_{Lmax} = 0.542$
$K_t = 1.27Nm/A$	$\gamma = 2$
$K_f = 1.0371Vs/rad$	$\Delta\beta = 1.86$
$K_b = 1.4324 \times 10^{-4}Nms/rad$	$p_p = 0.393rad$
$J_m = 0.01kgm^2$	$\rho = 998kg/m^3$
$-$	$A_p = 5.3093 \times 10^{-2}m^2$
$-$	$L = 0.127m$ and $R = 0.12m$

Figure 4 shows propeller angular speed and hydrodynamic load torque versus time for a fifty seconds period triangular wave input of command voltage. This voltage signal was utilized by Healey et al. (1995) to analyse the model steady-state response for both positive and negative values of voltage input command. To investigate the relation between propeller thrust and load torque, the data provided by the thruster model is depicted in Figure 5a. As it is shown, a linear function seems to be a good approximation. Using linear regression techniques to fit a straight line to the data, it is possible to model this relation as:

$$T = 17.069Q + 0.0049. \tag{19}$$

Therefore, the thrust can be estimated as:

$$\tilde{T} \approx 17.069\tilde{Q}. \tag{20}$$

Figure 5b shows simulation results for the predicted thrust when this linear static relation is applied to the previously obtained $\tilde{Q}$ data.

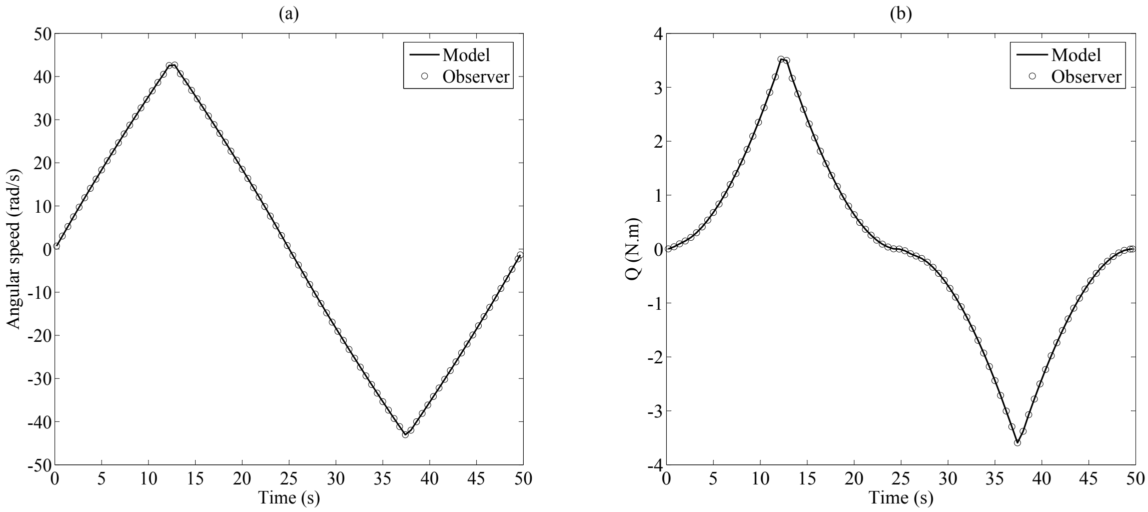

Figure 4. (a) Propeller angular speed versus time and (b) propeller load torque versus time. A voltage triangular wave with 50V of amplitude and period of 50s was applied to the DC motor.

To perform a transient analysis, a step voltage signal with 50V of amplitude was also used to test the proposed observer. Simulation results are shown in Figures 6 and 7.

All the results obtained in this section, shown that the observer produces good estimates of propeller angular speed and hydrodynamic load torque in both steady-state and transient regimes. In transient regime, the maximum observer error is less than 31% in thrust estimation as shown in Figure 7. This is due to the fact that $\tilde{T}$ is computed from the linear static relation in (20), which is not valid during the transient regime. Table 2 shows the percent estimation errors for propeller angular speed, propeller load torque and propeller thrust.

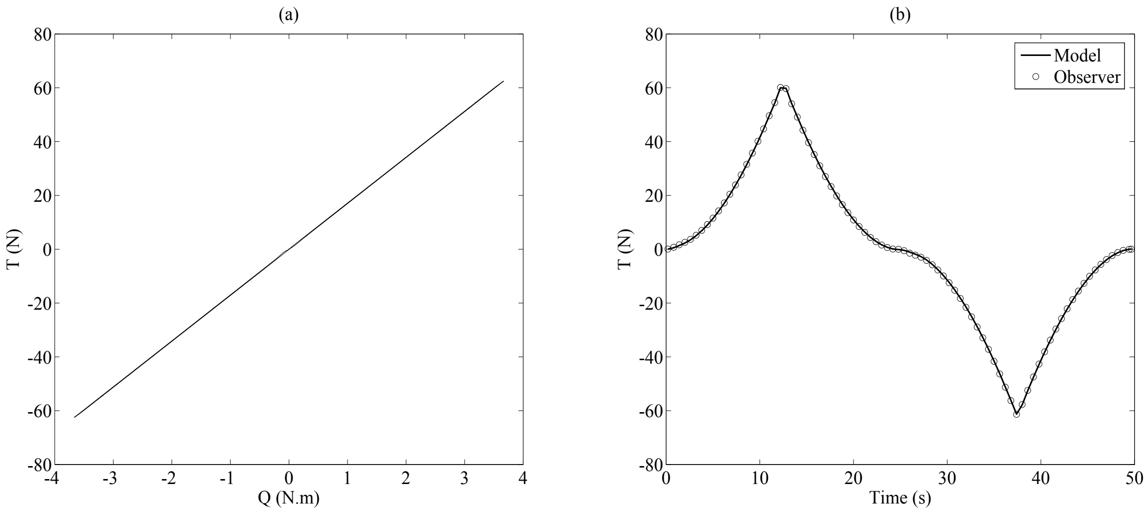

Figure 5. (a) Propeller thrust versus load torque and (b) propeller thrust versus time. A voltage triangular wave with 50V of amplitude and period of 50s was applied to the DC motor.

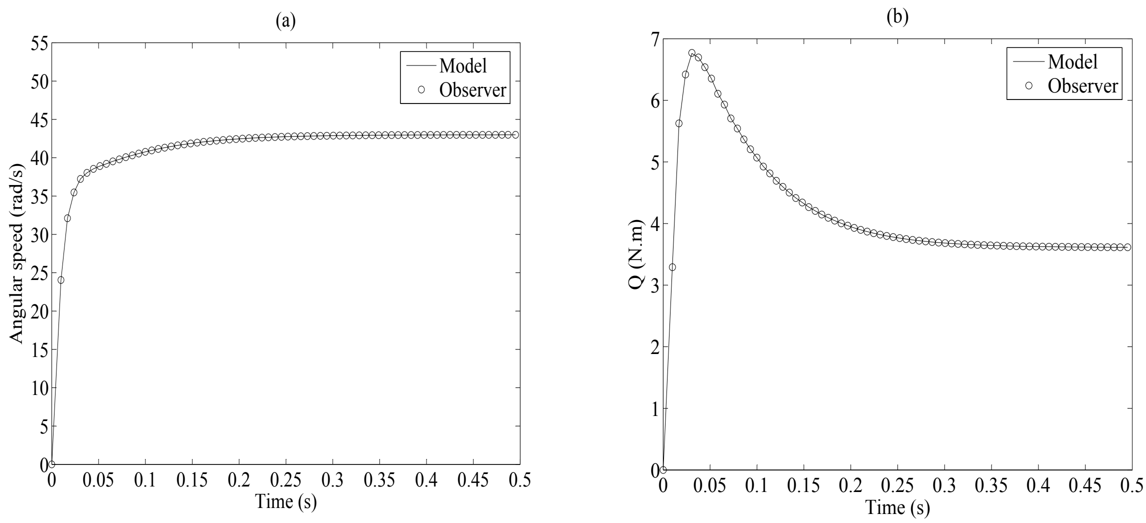

Figure 6. (a) Propeller angular speed versus time and (b) propeller load torque versus time. A step voltage with 50V of amplitude was applied to the DC motor.

Table 2. Percent estimation errors in relation to the maximum thruster model response

Variable	**Estimation errors (%)**	
	Steady-state regime	Transient regime
Propeller speed (rad/s)	$< 7.67 \times 10^{-6}$	$< 7.67 \times 10^{-6}$
Propeller load torque (N.m)	$< 7.52 \times 10^{-6}$	< 0.05
Propeller thrust (N)	< 0.02	< 31

6. CONCLUSIONS

In this paper, a thruster observer has been designed and analyzed. The observer is carried out by extending the classical observer theory by considering the propeller torque as an unknown input whose variation is much slower than the observer dynamics. Simulation results were presented that seems to indicate that accurate estimation of propeller angular speed and propeller torque in both steady-state and transient regimes is possible. In steady-state, the observer also estimates accurately the axial thrust developed by the thruster. The estimation scheme is very attractive since only two easily

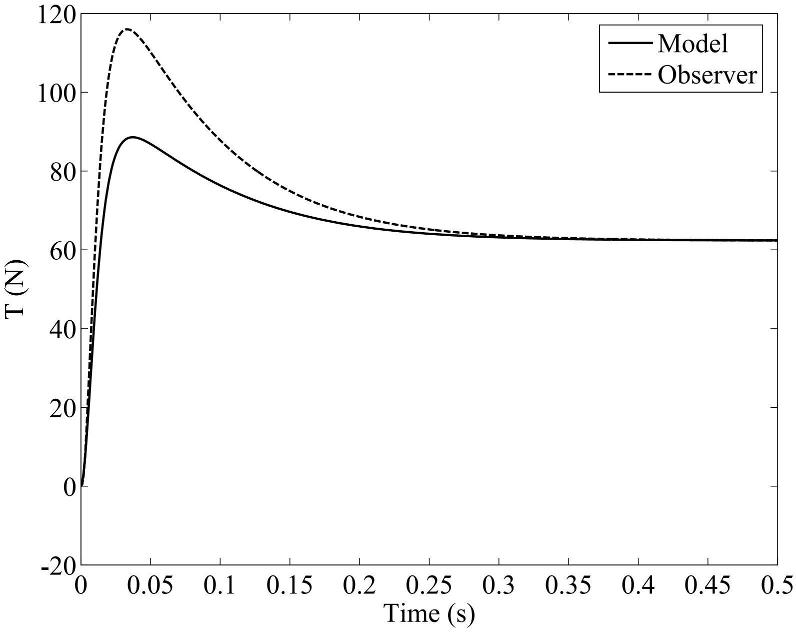

Figure 7. Propeller thrust versus time. A step voltage with 50V of amplitude was applied to the DC motor.

measurement signals are necessary: armature motor electrical current and voltage. Therefore the observer can be applied in speed sensorless DC drive thruster system to monitors the thruster performance. Experimental observer validation and robustness analysis would hence be a natural extension of the present work.

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8. Responsibility notice

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