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Adaptive Control for Ship Roll Motion with Fully Unknown Parameters

Sara Dadras, *Student Member, IEEE*, Hamid Reza Momeni, *Member, IEEE*, and Soudeh Dadras

***Abstract*— This paper is concerned with the problem of adaptive control for roll motion of ship as a nonlinear system with five equilibrium points which faces external disturbance. The system parameters are fully unknown. The purpose is to design a robust controller for this model with these properties, under the influence of external sinusoidal disturbances. The capabilities of the proposed controller are verified via simulations.**

I. Introduction

NONLINEAR systems may have multiple modes of behavior that are highly dependent on the input and initial conditions. Roll motions of ships is an example of nonlinear systems with five equilibrium points, three focus and two saddle points. Its model has uncertain parameters and it faces external disturbance a lot.

Roll motion [1] is an undesirable feature of the behavior of a ship in rough seas [2], and so it is natural to consider ways of reducing it. The most common devices for increasing roll damping are bilge keels. However, the effectiveness of keels is limited, and anti-roll tanks and fins are used when more control is required. Moreover, unlike keels, anti-roll tanks can be used when the ship is not underway [3].

At present, many control schemes for roll reducing have been studied [4],[5],[6]. Most of them are based on the exactly knowing of the system structure and parameters. But in practical situations, some or all of the system's parameters are unknown. Moreover, these parameters change from time to time. Therefore, the derivation of an adaptive controller for the control of roll motion of ship in the presence of unknown system parameters is an important issue.

Among the different nonlinear control techniques, much research works have been done to use adaptive methods [7] in order to improve the performance of the controlled systems [8],[9] and remedy the problems met in practical implementation of the controllers in presence of uncertainties and external disturbances. The adaptive control issue has been addressed for the asymptotic and exponential stability properties for nonlinear systems with uncertainties [10],[11].

The purpose of this paper is the development of an adaptive controller for regulating the state trajectories of the system with fully unknown parameters to the origin of the state space. Applying the Lyapunov stability theory, an adaptive control law is proposed. The stability and robustness of the proposed adaptive control algorithm are proven. State trajectory is designed to reach the origin in finite time.

The remainder of this paper is organized as follows: In Section 2, the system dynamics of the nonlinear system is described. In Section 3, the adaptive control scheme is briefly introduced, and stability analysis is given. In Section 4, computer simulation is also given for the purpose of illustration and verification. Finally conclusion is presented, in Section 5.

II. System Description

A good modeling can help to design an appropriate controller; a simplified mathematical model of the roll motions of ships is given by [3]:

$$\ddot{\theta} + \left(2\mu_1\dot{\theta} + \mu_3\dot{\theta}^3\right) + \left(\omega_0^2\theta + \alpha_3\theta^3 + \alpha_5\theta^5\right) = u \tag{1}$$

where θ is the roll angle, the α_i are nonlinear coefficients, μ_1 is the linear damping coefficient, and μ_3 is the nonlinear damping coefficient and u is the control input. The nominal system parameters have the following values.

$$\omega_0 = 5.278,\ \ \alpha_3 = -1.402\omega_0^2,\ \ \alpha_5 = 0.271\omega_0^2 \tag{2}$$

Therefore the equilibrium point will be the same as below:

$$\begin{cases} x_{2e} = 0 \\ x_{1e} = 0, \left(\dfrac{-\alpha_3 \pm \sqrt{\alpha_3^2 - 4\omega_0^2\alpha_5}}{2\alpha_5}\right)^{\frac{1}{2}} = 0, \pm 0.924, \pm 2.078 \end{cases} \tag{3}$$

By using linearization techniques the linearized model will be as (4)

$$\dot{X}_e = \begin{bmatrix} 0 & 1 \\ -(\omega_0^2 + 3\alpha_3 x_{1e}^2 + 5\alpha_5 x_{1e}^4) & -(2\mu_1 + 3\mu_3 x_{2e}^2) \end{bmatrix} X_e + \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

$$y = [1 \quad 0]X \tag{4}$$

Resulting in the following eigenvalues :

$$\lambda_e = -(\mu_1 + 1.5\mu_3 x_{2e}^2) \pm \sqrt{(\mu_1 + 1.5\mu_3 x_{2e}^2)^2 - (\omega_0^2 + 3\alpha_3 x_{1e}^2 + 5\alpha_5 x_{1e}^4)} \tag{5}$$

Sara Dadras is with the ECE Department, Tarbiat Modares University, Tehran, Iran (corresponding author, phone: +98-21-8288-3309; fax: +98-21-8288-3375; e-mail: s_dadras@modares.ac.ir).
Hamid Reza Momeni is with the ECE Department, Tarbiat Modares University, Tehran, Iran (e-mail: momeni_h@modares.ac.ir).
Soudeh Dadras is graduated from the ECE Department, Shiraz University, Shiraz, Iran (e-mail: soudehdadras@yahoo.com).

So eigenvalues at equilibrium points will be as it has been shown in Table 1.

TABLE I. EIGENVALUES AT EQUILIBRIUM POINT

Type	λ_e	(x_{1e}, x_{2e})
Focus	$\lambda_e = -\mu_1 \pm \sqrt{\mu_1^2 - 225.735}$	(-2.078,0)
Saddle	$\lambda_e = -\mu_1 \pm \sqrt{\mu_1^2 + 44.663}$	(-0.924,0)
Focus	$\lambda_e = -\mu_1 \pm \sqrt{\mu_1^2 - 27.857}$	(0,0)
Saddle	$\lambda_e = -\mu_1 \pm \sqrt{\mu_1^2 + 44.663}$	(0.924,0)
Focus	$\lambda_e = -\mu_1 \pm \sqrt{\mu_1^2 - 225.735}$	(2.078,0)

Types of equilibrium points show effect of initial value and external disturbance in determining final value. The objective of this paper is to introduce a control law that will have the origin as a globally stable equilibrium point to force the system to approach the origin from any initial condition while exhibiting a satisfactory transient performance. The following section introduces a strategy to design a controller that dictates a predefined transient behavior. Fig. 1 illustrates the behavior of uncontrolled system.

In this paper, the following problem is considered: For nonlinear system (1) with fully unknown parameter, how to design controller u to globally stabilize the origin. Different from the existing results, an efficient adaptive feedback controller will be introduced.

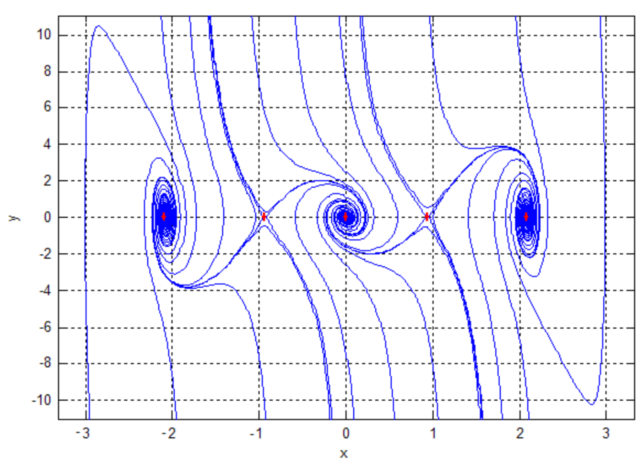

Figure 1. Uncontrolled system.

III. CONTROLLER DESIGN

In this section an adaptive controller is designed to have the origin as a globally stable equilibrium point to regulate the system around the origin from any initial condition in spite of the fully unknown parameters and existence of external disturbance. The following section introduces a strategy to design the controller.

To solve the problem formulated in (1), we rewrite the system equations

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ -(\alpha + \alpha_3 x_1^2 + \alpha_5 x_1^4) & -(\beta + \mu_3 x_2^2) \end{bmatrix} X + \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (6)$$

where

$$\alpha = \omega_0^2,\ \beta = 2\mu_1 \quad (7)$$

So, the proposed control law u_1, u_2 is obtained

$$\begin{cases} u_1 = -k_1 x_1 - x_2 \\ u_2 = -k_2 x_2 + \hat{\alpha} x_1 + \hat{\alpha}_3 x_1^3 + \hat{\alpha}_5 x_1^5 + \hat{\beta} x_2 + \hat{\mu}_3 x_2^3 \end{cases} \quad (8)$$

where k_1 and k_2 are positive constants and the adaptive law for parameter estimation is derived in the following paragraphs which is

$$\dot{\hat{\alpha}} = -x_1 x_2$$
$$\dot{\hat{\alpha}}_3 = -x_1^3 x_2$$
$$\dot{\hat{\alpha}}_5 = -x_1^5 x_2$$
$$\dot{\hat{\beta}} = -x_2^2$$
$$\dot{\hat{\mu}}_3 = -x_2^4 \quad (9)$$

The proposed adaptive control scheme mentioned above above will guarantee the global asymptotical stability for system (4), and is proven in Theorem 1.

Theorem 1. Considering the system dynamics (4), if this system is controlled by $u(t)$ as in Equation (8) with adaptive law in Equation (9). Then the controlled nonlinear system is globally asymptotically stable.

Proof. Let

$$\tilde{\alpha} = \alpha - \hat{\alpha}$$
$$\tilde{\alpha}_3 = \alpha_3 - \hat{\alpha}_3$$
$$\tilde{\alpha}_5 = \alpha_5 - \hat{\alpha}_5$$
$$\tilde{\beta} = \beta - \hat{\beta}$$
$$\tilde{\mu}_3 = \mu_3 - \hat{\mu}_3 \quad (10)$$

where $\hat{\alpha}$ is the estimation for α and so for $\hat{\alpha}_3$, $\hat{\alpha}_5$, $\hat{\beta}$ and $\hat{\mu}_3$. Thus the following expression holds:

$$\dot{\tilde{\alpha}} = -\dot{\hat{\alpha}}$$
$$\dot{\tilde{\alpha}}_3 = -\dot{\hat{\alpha}}_3$$

$$\dot{\tilde{\alpha}}_5 = -\dot{\hat{\alpha}}_5$$
$$\dot{\tilde{\beta}} = -\dot{\hat{\beta}}$$
$$\dot{\tilde{\mu}}_3 = -\dot{\hat{\mu}}_3 \tag{11}$$

Consider the following Lyapunov function candidate

$$V(t) = \frac{1}{2}(X^T X + \tilde{\alpha}^2 + \tilde{\alpha}_3^2 + \tilde{\alpha}_5^2 + \tilde{\beta}^2 + \tilde{\mu}_3^2) \tag{12}$$

It is clear that V is a positive definite function, then taking the derivative of $V(t)$ with respect to time t, one has

$$\begin{aligned} \dot{V}(t) &= x_1\dot{x}_1 + x_2\dot{x}_2 + \tilde{\alpha}(\dot{\tilde{\alpha}}) + \tilde{\alpha}_3(\dot{\tilde{\alpha}}_3) + \tilde{\alpha}_5(\dot{\tilde{\alpha}}_5) \\ &\quad + \tilde{\beta}(\dot{\tilde{\beta}}) + \tilde{\mu}_3(\dot{\tilde{\mu}}_3) \\ &= x_1\dot{x}_1 + x_2\dot{x}_2 - (\alpha - \hat{\alpha})(\dot{\hat{\alpha}}) - (\alpha_3 - \hat{\alpha}_3)(\dot{\hat{\alpha}}_3) \\ &\quad - (\alpha_5 - \hat{\alpha}_5)(\dot{\hat{\alpha}}_5) - (\beta - \hat{\beta})(\dot{\hat{\beta}}) - (\mu_3 - \hat{\mu}_3)(\dot{\hat{\mu}}_3) \end{aligned} \tag{13}$$

Introducing (8) and (9) into Equation (13) yields

$$\begin{aligned} \dot{V}(t) &= x_1\dot{x}_1 + x_2\dot{x}_2 - (\alpha - \hat{\alpha})(-x_1x_2) \\ &\quad - (\alpha_3 - \hat{\alpha}_3)(-x_1^3x_2) \\ &\quad - (\alpha_5 - \hat{\alpha}_5)(-x_1^5x_2) - (\beta - \hat{\beta})(-x_2^2) \\ &\quad - (\mu_3 - \hat{\mu}_3)(-x_2^4) \\ &= x_1(x_2 + u_1) \\ &\quad + x_2(-\alpha x_1 - \alpha_3 x_1^3 - \alpha_5 x_1^5 - \beta x_2 - \mu_3 x_2^3 + u_2) \\ &\quad - (\alpha - \hat{\alpha})(-x_1x_2) - (\alpha_3 - \hat{\alpha}_3)(-x_1^3x_2) \\ &\quad - (\alpha_5 - \hat{\alpha}_5)(-x_1^5x_2) - (\beta - \hat{\beta})(-x_2^2) \\ &\quad - (\mu_3 - \hat{\mu}_3)(-x_2^4) \end{aligned}$$
$$\dot{V}(t) = -k_1x_1^2 - k_2x_2^2 \tag{14}$$

Therefore, the closed loop system is asymptotically stable and the proof is achieved completely. □

Remark 1. Compared with the existing literatures investigating the control problem of nonlinear systems, the proposed controller (8) and (9) is fairly simple.

In the next section results of the proposed algorithm are shown.

IV. Simulation Results

This section shows the simulation results. We have considered two different cases. First case shows results of implementing controller on nonlinear model with nominal values, without external disturbance. Second one describes results of implementing controller on nonlinear model with nominal parameters and sinusoidal external disturbance.

In this part, external disturbance is equal to $5sin(0.2t)$ which is added to the second state and initial value of the states are $X_0 = [-3 \quad 2]^T$, and $\hat{\alpha}_0 = 0.1$, $\hat{\alpha}_{3_0} = 0.3, \hat{\alpha}_{5_0} = 0.5, \hat{\beta}_0 = 0.7$, $\hat{\mu}_{3_0} = 0.9$, and $k_1 = k_2$=5.

The results of the adaptive control algorithm are shown in Figure 2. In order to make comparison, we plot the time response of the uncontrolled system simultaneously. As it has shown in Figure 2, this initial value in our model causes going to the point (-2.078, 0) but here controller guide it to the origin.

The time responses of adaptation parameters without external disturbance are shown in Figure 3.

From the simulation results, we can see that the adaptive control scheme can estimate the unknown parameters of the system very fast and the states regulate well and the system have no steady state error. The settling time is perfect due to this control law and there is no overshoot or undershoot in output (x_1).

Figure 4 shows the time response of both controlled and uncontrolled system in presence of external disturbance. It can be seen a little increase in the settling time but it is still perfect and the closed loop system has a desired performance. The time responses of adaptation parameters in presence of external disturbance are shown in Figure 5.

State trajectories of the controlled system in presence of disturbance for different values of initial conditions are depicted in Fig. 6. It is clear that the equilibrium point E(0,0)

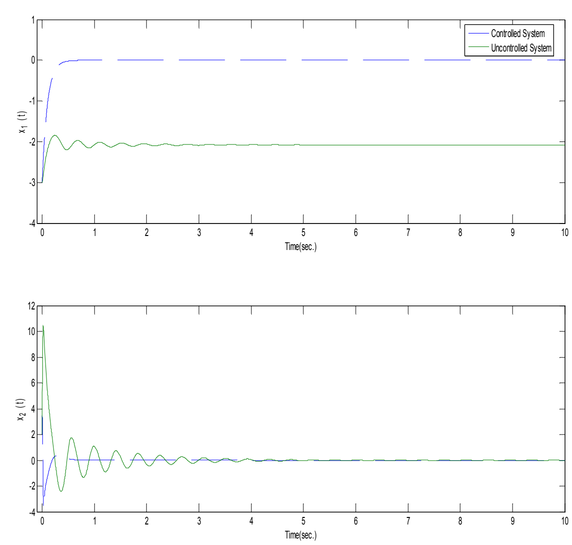

Figure 2. The time response of the controlled system states (dashed line) and the uncontrolled system states (solid line), without external disturbance.

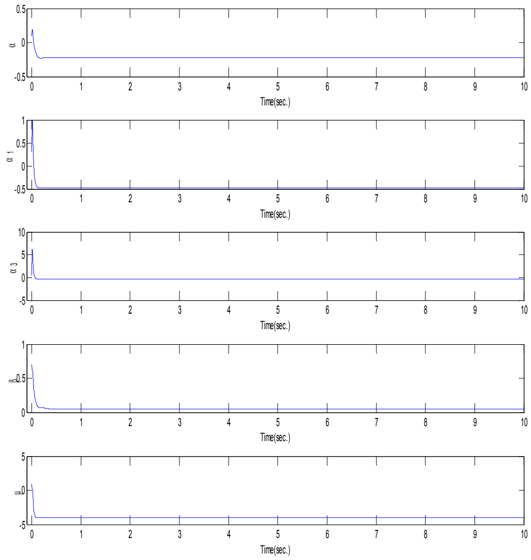

Figure 3. The time response of adaptation parameters (without external disturbance).

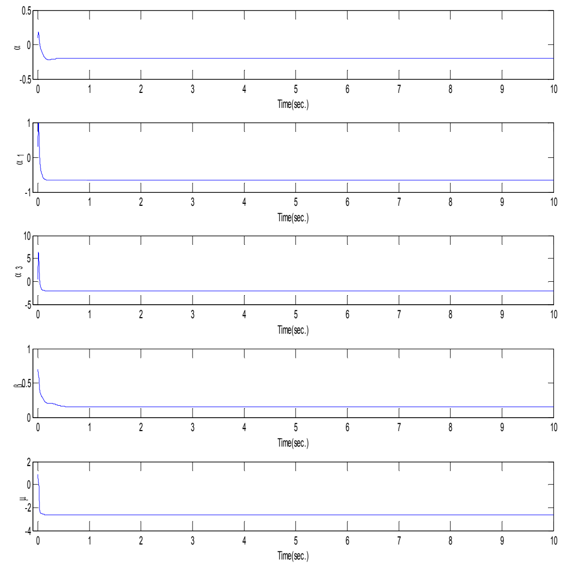

Figure 5. The time response of adaptation parameters (with external disturbance).

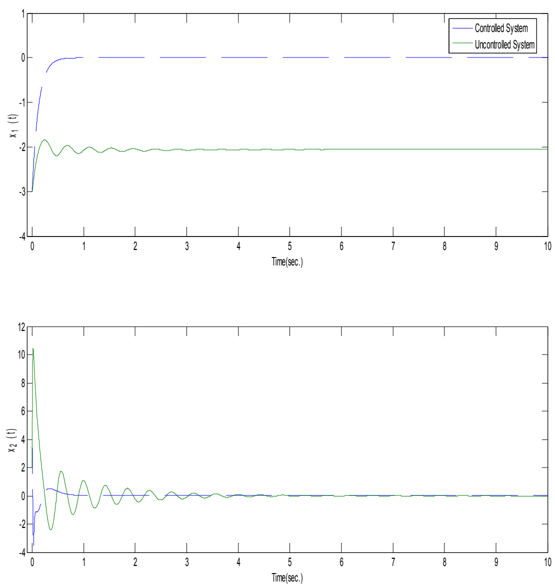

Figure 4. The time response of the controlled system states (dashed line) and the uncontrolled system states (solid line), with external disturbance.

is globally asymptotically stable and the controller is robust in presence of the external disturbance.

Simulations show that the obtained theoretic results are feasible and efficient for controlling roll motion of the ship. Although conditions are different in a wide range but our robust nonlinear controller has produced a stable output which can handle parameter uncertainty and external disturbance.

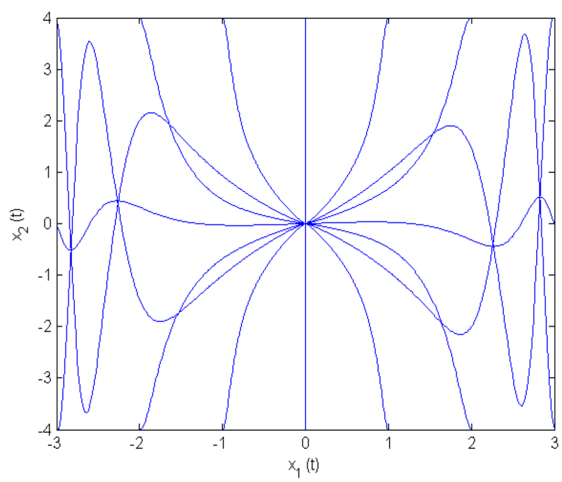

Figure 6. State trajectories of the controlled system in presence of disturbance.

V. Conclusion

In this paper, an effective adaptive law is presented to globally stabilize the origin for a nonlinear system that describes the dynamics of roll motion of ship. First estimation law based on adaptive rules is proposed to handle the unknown parameter problem. Then by applying appropriate control signal based on adaptive update law, a continuous control signal is achieved and stability of the system is guaranteed. Both the theoretical studies and the simulation results demonstrate that not only the adaptive control proposed in this paper guides the response to the origin as a global equilibrium point but also external disturbance can not disturb convergence. So this controller can handle inaccuracy and external disturbance.

REFERENCES

[1] E. Lefeber, K. Y. Pettersen, and H. Nijmeijer, "Tracking control of underactuated ship", IEEE Trans. Control Systems Technology, vol. 11, pp. 52-61, January 2003.

[2] S. L. Chen, and W. C. Hsu, "Fuzzy sliding mode control for ship roll stabilization", Asian Journal of Control, vol. 5, pp. 187-194, June 2003.

[3] A. Zaher, "Nonlinear control of systems with multiple equilibria and unknown sinusoidal disturbance", Communications in Nonlinear Science and Numerical Simulation, vol. 12, pp. 1518-1533, 2007.

[4] X.j. Yang, and X. R. Zhao, "Self-organization neural-net control of ship's horizontal motion", Journal of Physics: onference Series, vol. 48, pp. 1284-1288, 2006.

[5] D. Liu, and H. D. Patino, "Adaptive critic designs for self-learning ship steering control", Proceedings of IEEE International Symposium on Inteligent control/Intelligent Systems and Semiotics, Cambridge, MA., Sep. 15-17, 1999.

[6] K. D. Do, J. Pan, and Z. P. Jiang, "Robust adaptive control of under actuated ships on a linear course with comfort", Ocean Engineering, vol.30, pp. 2201-2225, 2003.

[7] H. Khalil, Nonlinear systems, 3rd ed., London: Prentice Hall, 2002.

[8] C. Hua, and X. Guan, "Adaptive control of chaotic systems", Chaos, Solitons ans Fractals, vol. 22, pp. 55-60, 2004.

[9] M. D. L. Sen, "Robust adaptive control of linear time-delay systems with point time-varying delays via multiestimation", Applied Mathematical Modelling, vol. 33, pp. 959-977, 2009.

[10] X. Zheng, and Y. Wu, "Adaptive output feedback stabilization for nonholonomic systems with strong nonlinear drifts," Nonlinear Analysis, vol. 70, pp. 904-920, 2009.

[11] J. E. Soltine, W. Li, Applied nonlinear control, Englewood Cliffs, NJ: Prentice Hall, 1991.