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AN ENHANCED SLIDING MODE CONTROL METHOD FOR THE WAVE COMPENSATION SYSTEM OF SHIP-MOUNTED CRANES WITH ROLL MOTIONS AND PARAMETRIC UNCERTAINTIES

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Key words: Ship-mounted crane, wave compensation, persistent disturbances, parametric uncertainties, adaptive control method.

ABSTRACT

Ship-mounted cranes are widely used in offshore constructions, resource exploitation and marine salvages, to transfer payloads. Due to serious sea conditions, unexpected motions of the ships caused by the wave will probably pose serious efficiency and security issues. Thus, the wave compensation system has become necessary equipment for the ship-mounted crane. But wave-induced motions of the ship, parametric uncertainties and nonlinearities remain challenges for control of wave compensation systems, which needs to be solved urgently. In this paper, the mathematical model of the wave compensation system is established firstly. Then, a sliding mode controller is presented and the stability is proved considering ship roll movement. To deal with the unknown parameters of the system, the radial basis function (RBF) neural network is utilized in conjunction with sliding mode controller to construct an adaptive control strategy. Finally, both simulation and experiment results are included to verify the effectiveness of the proposed control strategy. The proposed control approach has better adaptability and greater robustness without chattering phenomenon, which can provides useful reference for other underactuated system facing persistent disturbances and parametric uncertainties.

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I. INTRODUCTION

With the development of the ocean engineering and automation, ship mounted crane, which is normally utilized for marine cargo transshipment and salvage, is becoming a hot topic in many research fields. As an important transportation tool for cargo transfer and salvage, the performance of the ship mounted crane, which is mainly about the human cost, working efficiency and production security, is significant. [1-3] However, it is generally accepted that the wave compensation problems for the ship mounted crane in complicated harsh sea conditions are very challenging.

The researchers have proposed variety of control strategies for the wave compensation systems (Woodacre et al., 2015). Kuchler et al. (2011) proposed an active compensation system for the forces induced by vertical motion of the vessel which is known as the first nonlinear control scheme with motion prediction system. Do and Pan (2008) presented a novel method which is based on an electro-hydraulic system driven by a double rod actuator and also a nonlinear controller is proposed for active heave compensation. Sun et al. (2018) proposed a novel nonlinear stabilizing control strategy for the ship mounted crane systems by considering the roll and heave motion compensation of the ship. Persaud et al. (2019) developed a passive heave compensator for a scientific research ship numerically. Vaerno et al. (2019) investigated the compensation methods on the environmental loads and four presented methods were also compared numerically and experimentally as comparison group. Besides these common compensation system listed above, there are also some intelligent controllers that utilized to wave compensation of the ship mounted crane. Rong et al. (2019) proposed a hybrid control system, which is designed to compensate the wave induced ship's relative motion, consists of three PD controllers and a fuzzy controller. Yu et al. (2019) presented a solution for active heave compensation systems by variable structure

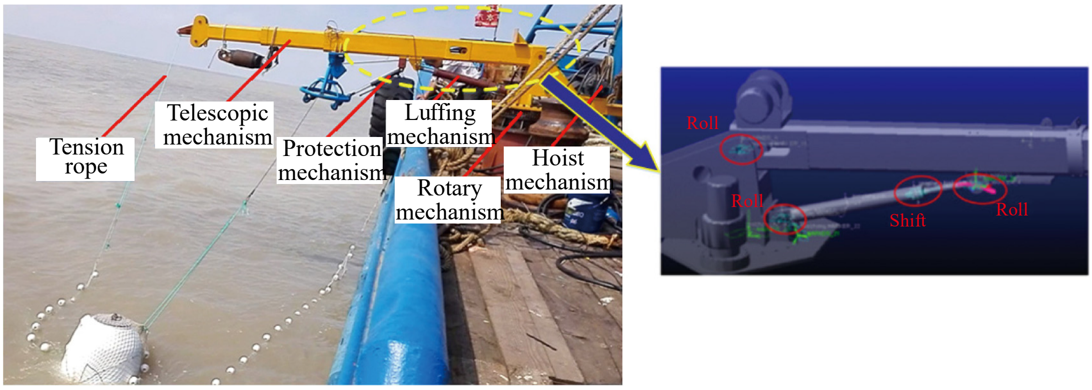

Fig. 1. Ship-mounted crane systems

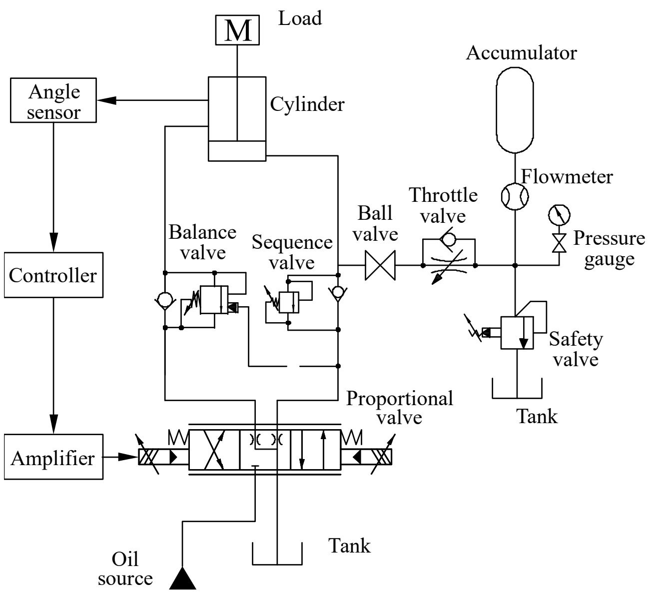

Fig. 2. Hydraulic Scheme of wave compensation system

control. The effectiveness of the designed controller was compared between the variable structure control method and trajectory planning control method. The theoretical and experimental analyses were also presented to show the proposed variable structure controller is more effective. Sun et al. (2017) proposed a double-layer sliding mode control law to eliminate the influence of the sea condition on the cargo sway. Both the simulations and experiments are included to show the effectiveness of the proposed control law. Owing to the complexity of the ocean environment, the wave-induced roll motion affects the maneuverability of the ship-mounted cranes greatly. Moreover, some parameters of the mechanical equipment are inevitably difficult to be described by accurate mathematical models such as the mass and the spoke width of the valve spool. In order to satisfy the control performance of the ship mounted crane, the robustness of the control system should be ensured.

To tackle the influence of persistent disturbances and parametric uncertainties, sliding model control (SMC), as one of the robust control methods (Li et al., 2019; Chen and Sun, 2020; Sun et al., 2020; Sun et al., 2020), is a proper solution with strong robustness. In recent years, SMC has been proved to be successful in various applications (Wang et al., 2018; Kim and Hong, 2019; Sun et al., 2019; Wang et al., 2020; Zhang and Jing, 2020). Wang et al. (2018) proposed a first- and higher-order field-oriented sliding mode controller for permanent magnet AC motors with better dynamic torque and speed response. Kim et al. (2019) designed a novel sliding mode controller with two adaptation laws for offshore container crane. The asymptotic stability of the proposed controller is proven using Lyapunov method. Sun et al. (2019) developed a sliding model control with neural-fuzzy approximator. The proposed control strategy can approximate unknown parameters on-line effectively. Zhang and Jing (2020) proposed an adaptive fuzzy SMC method for half-car active suspension systems, which can deal with input dead zones and saturations effectively. Wang et al. (2020) presented a new adaptive sliding mode fault-tolerant fuzzy tracking control method for unmanned marine vehicles. Thus the outstanding performance with insensitive to external disturbances and parametric uncertainties of SMC can be utilized for nonlinear systems, which makes it possible to apply it in ship mounted crane systems.

In previous studies, the problems of the nonlinear control, which are mainly about the persistent disturbances of the ship-mounted cranes and uncertainty of system parameters, have not been solved in a proper way. In this paper, a dynamic model of ship-borne manipulator based on the variable amplitude control oil circuit had been established firstly. Next, a modified SMC strategy with RBF neural network is proposed to the wave compensation system. The chattering phenomenon was studied and had been reduced significantly. Additionally, the stability of the system had been analyzed and the results proves that the system state tracks the desired target signal and tracking error $e(t)$ tends to zero. Finally, simulations and experiments are performed to verify the validity and robustness of the presented method. The main contribution of this paper is summarized as follows:

(1) The proposed adaptive controller can ensure better tracking performance of the wave compensation system tackling the persistent disturbances of roll motions
(2) The designed method does not require the accurate mathematical models since the uncertain parameters of the wave compensation system can be approximated on-line.
(3) As shown in experimental results, the proposed method had a increased control performance in wave-induced roll motion environment without chattering phenomenon.

The rest of this paper is organized as follows. In section 2, the coupling dynamic model of valve-controlled wave compensation system is established. Section 3 designs a modified sliding mode control strategy with RBF to remove the requirement of accurate system parameters and attenuate chattering. Simulation results are provided in Section 4. Experimental results are shown in Section 5. Section 6 gives the conclusions and further works of this paper.

II. DYNAMIC MODEL

The hydraulic system control loop of the ship-borne the manipulator for the ship-mounted crane is shown in Fig. 2. The angle and displacement sensors are utilized to collect the displacement and angle signals of the amplitude-changing cylinder. The sliding valve opening is adjusted by the controller and power amplifier.

Compared with the working pressure, the pressure in the rod chamber of the cylinder can be neglected, and the force balance equation of the piston rod of the cylinder is given as follows:

$$pA = m_t\ddot{x} + B_P\dot{x} + k_z x + F_L\,, \tag{1}$$

where, p denotes the working pressure; A is the action area of rodless cavity; m_t represents the mass of the piston; x denotes the displacement of pistol; B_P denotes the viscosity damping coefficient; k_z denotes the spring stiffness.

The cylinder flow continuity equation can be represented as follows:

$$Q_L = A\dot{x} + C_i p, \qquad Q_L = Q_1 + Q_X\,, \tag{2}$$

where, Q_L denotes the cylinder flow rate; Q_1 represents the orifice flow; Q_X is the accumulator flow; C_i denotes the cylinder leakage coefficient. The flow rate equation of spool valve can be expressed as follows:

$$\begin{cases} Q_1 = C_d w x_v \sqrt{\dfrac{2}{\rho}\left(p_S - p_1\right)} = k_q x_v \\ x_v = k_v \cdot \mu \end{cases} \tag{3}$$

where, C_d is the valve orifice flow coefficient; w denotes the valve orifice area gradient; x_v is the valve core displacement; k_v is the valve core proportional coefficient; μ denotes the current signal of valve core; ρ is the oil density; p_S is the oil source pressure; p_1 is the pressure of valve core chamber; k_q is the flow gain coefficient of valve orifice.

The accumulator dynamic equation is given by

$$\begin{cases} p \cdot A_a = k_a \cdot x_a \\ Q_X = \dot{x}_a \cdot A_a \end{cases} \tag{4}$$

where, A_a is the action area of the accumulator; k_a is the gas stiffness coefficient; x_a is the gas displacement in the accumulator.

The state space expression of the valve-controlled cylinder system obtained by simultaneous equations (1) to (4) is listed as follows:

$$\begin{cases} p.A = m_t \cdot \ddot{x} + B_P \cdot \dot{x} + k_z \cdot x + F_L \\ A \cdot \dot{x} + C_i \cdot p = k_q \cdot x_v + \dot{P} \cdot \dfrac{A_a^{\,2}}{k_a} \\ x_v = k_v \cdot \mu \end{cases} \tag{5}$$

According to organizing equation (5), the equation (6) is given by

$$\begin{aligned} \dddot{x} = &-(\frac{B_P}{m_t} - \frac{C_i \cdot k_a}{A_a^{\,2}})\ddot{x} - (\frac{k_z}{m_t} - \frac{C_i \cdot k_a \cdot B_P}{m_t \cdot A_a^{\,2}} - \frac{k_a \cdot A^2}{m_t \cdot A_a^{\,2}})\dot{x} \\ &+ \frac{C_i \cdot k_a \cdot k_z}{m_t \cdot A_a^{\,2}} x - \frac{k_a \cdot k_q \cdot k_v \cdot A}{m_t \cdot A_a^{\,2}} \mu + \frac{k_a \cdot C_i \cdot F_L}{m_t \cdot A_a^{\,2}} \end{aligned} \tag{6}$$

Assuming the state of the system is $x_1 = x$, $x_2 = \dot{x}$, $x_3 = \ddot{x}$, the dynamic model of the valve-controlled wave compensation system is

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3 + g\mu + d \\ x = x_1 \end{cases} \tag{7}$$

where

$$\begin{cases} \theta_1 = \dfrac{C_i \cdot k_a \cdot k_z}{m_t \cdot A_a^{\,2}} \\ \theta_2 = -(\dfrac{k_z}{m_t} - \dfrac{C_i \cdot k_a \cdot B_P}{m_t \cdot A_a^{\,2}} - \dfrac{k_a \cdot A^2}{m_t \cdot A_a^{\,2}}) \\ \theta_3 = -(\dfrac{B_P}{m_t} - \dfrac{C_i \cdot k_a}{A_a^{\,2}}) \\ g = -\dfrac{k_a \cdot k_q \cdot k_v \cdot A}{m_t \cdot A_a^{\,2}} \\ d = \dfrac{k_a \cdot C_i \cdot F_L}{m_t \cdot A_a^{\,2}} \end{cases} \tag{8}$$

III. AN ENHANCED SLIDING MODE CONTROL METHOD DESIGN

Considering the dynamic model of valve-controlled cylinder system (Landet et al., 2012; Kilic et al., 2012; Linjama et al., 2016), the traditional sliding mode control method is designed to achieve the stable hovering state of the fixed angle of the manipulator under the influence of the external disturbance. In other words, the state $x_1(t)$ of the system can track the sine-cosine wave compensation motion of salvage equipment under complex sea condition, and set the target position signal y_d of sine-cosine compensation motion, which can make the position tracking error $|x_1(t)-y_d|$ converge to the neighborhood of zero.

The traditional sliding model controller requires that the system parameters are accurate and the chattering phenomenon may occur in the control inputs. In order to solve the problems and better deal with the uncertainties and parameter perturbations during sea lifting, a sliding mode controller with RBF neural network is proposed.

The dynamic model of the ship-borne the manipulator with wave compensation system of the ship-mounted crane with uncertain parameters is provided as follows.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = \theta f(x) + \beta g(x) u_s + d \\ y = x_1 \end{cases} \tag{10}$$

where, x_1 and x_2 are the state variables of salvage equipment under complex sea condition (i.e. the value and derivatives of the amplitude-changing cylinder of the manipulator); $d(t)$ is the load of the external manipulator; μ is the control system signal input; y is the angle of the manipulator; $f(x)$ and $g(x)$ are known functions of the hydraulic system, and for any x, $\beta g(\mathrm{x}) \neq 0$; θ and β are uncertain parameters for salvage luffing mechanism.

A novel sliding mode tracking controller is designed to make the displacement of the cylinder of the system track the desired trajectory y_d of sine-cosine compensation.

$$\lim_{t\to\infty}(y - y_d) = 0$$

The system error can be defined as follows:

$$e = y - y_d \tag{11}$$

Based on (10), the sliding mode manifold is proposed as below:

$$s \triangleq \{(e,\dot{e},\ddot{e}) \,|\, k_1 e + k_2 \dot{e} + \ddot{e} = 0\} \tag{12}$$

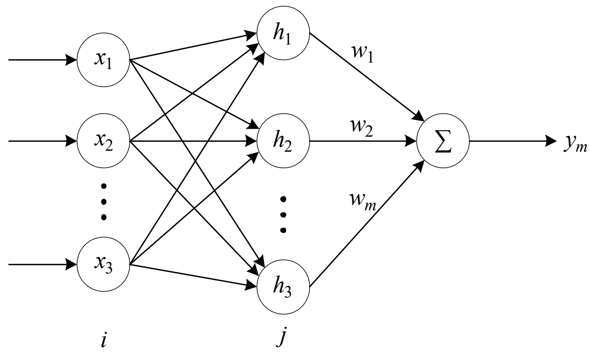

Fig. 3. RBF Neural Network

where, $k_1,\ k_2 \in R^+$ is the positive constant.

The derivation of (12) is calculated as follows:

$$\begin{aligned} \dot{s} &= k_1(\dot{y} - \dot{y}_d) + k_2(\ddot{x}_1 - \ddot{y}_d) + (\dddot{x}_1 - \dddot{y}_d) \\ &= k_1\dot{e} + k_2\ddot{e} + \theta f(x) + \beta g(x) u_s(t) + d - \dddot{y}_d \end{aligned} \tag{13}$$

The conventional sliding mode controller can be designed as below:

$$\begin{aligned} &u_s(x,t) = \\ &\frac{1}{\beta g(x)}\left[-\theta f(x) + \dddot{y}_d - k_1\dot{e} - k_2\ddot{e} - d - \eta\,\mathrm{sgn}(s) - \mu s\right] \end{aligned} \tag{14}$$

where, $\mathrm{sgn}(\bullet)$ is the signum function, and, η is a positive coefficient, μ denotes a positive control parameter.

The Lyapunov candidate function is constructed as follows:

$$V(x) = \frac{1}{2}s^2 \tag{15}$$

It is obvious that $V(x) \geq 0$. By taking the time derivative of $V(x)$ in (15), we can get：

$$\begin{aligned} \dot{V}(x) &= s \cdot \dot{s} = -s \cdot \eta\,\mathrm{sgn}(s) - \mu \cdot s^2 \\ &= -\eta|s| - \mu \cdot s^2 \leq 0 \end{aligned} \tag{16}$$

It is easy to prove that the system is stable with the conventional sliding mode controller by utilizing the Lyapunov analysis method (Tuan et al., 2015; Qian et al., 2019; Tuan et al., 2019).

However, in wave compensation system of ship-mounted cranes, $\theta f(x)$ and $\beta g(x)$ are uncertain, which will deteriorate the control performance or even lost stability. We are motivated to develop an on-line approximator to learn $\theta f(x)$ and $\beta g(x)$ based on RBF neural network. The structure of RBF neural network can be shown in Fig. 3.

The input and output of RBF neural network can be obtained as follows.

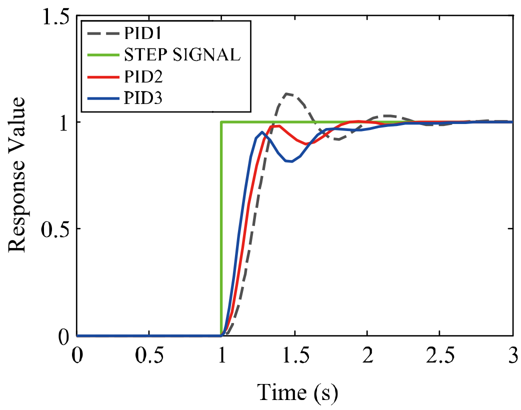

Fig. 4. Step response with PID controllers

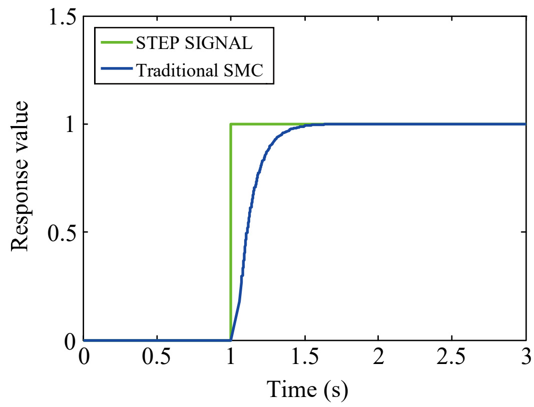

Fig. 5. Step response with SMC

$$h_j = \exp\left(\frac{\left\|\boldsymbol{x}-\boldsymbol{c}_j\right\|^2}{2b_j^2}\right) \tag{17}$$

$$\theta f(x) = \varepsilon_f + \boldsymbol{W}^{*T}\boldsymbol{h}_f(\boldsymbol{x}), \quad \beta g(x) = \varepsilon_g + \boldsymbol{L}^{*T}\boldsymbol{h}_g(\boldsymbol{x}) \tag{18}$$

where, $\boldsymbol{h} = \left[h_j\right]^{\mathrm{T}}$ is the output vector of the Gaussian basis function; $\boldsymbol{W}^*$ denotes the ideal weights of $\theta f(x)$; $\boldsymbol{L}^*$ represents ideal weights of $\beta g(x)$; $\boldsymbol{x} = \left[x_1 \quad x_2 \quad x_3\right]^{\mathrm{T}}$ denotes the input vector; j represents the node number of the hidden layer; $\varepsilon_f, \varepsilon_g$ are approximation errors of the RBF neural network respectively, which satisfy: $\left|\varepsilon_f\right| \le \varepsilon_{Mf}$, $\left|\varepsilon_g\right| \le \varepsilon_{Mg}$.

The output of RBF neural network can be written as follows:

$$\theta \hat{f}(\boldsymbol{x}) = \hat{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{h}_f(\boldsymbol{x}), \quad \beta \hat{g}(\boldsymbol{x}) = \hat{\boldsymbol{L}}^{\mathrm{T}}\boldsymbol{h}_g(\boldsymbol{x}) \tag{19}$$

where, $\boldsymbol{h}_f(\boldsymbol{x})$ and $\boldsymbol{h}_g(\boldsymbol{x})$ denote the Koski functions.

Combined with variable boundary layer [19-20], the proposed adaptive control law can be abstained as follows:

$$u_m(\mathbf{x},t) = \frac{1}{1/2s\left\|\boldsymbol{L}^*\right\|^2\boldsymbol{h}_g^{\mathrm{T}}\boldsymbol{h}_g}\left[-\frac{1}{2}s\left\|\boldsymbol{W}^*\right\|^2\boldsymbol{h}_f^{\mathrm{T}}\boldsymbol{h}_f + \ddot{y}_d - k_1\dot{e} - k_2\ddot{e} - d - \eta sat(s) - \mu s\right] \tag{20}$$

$$sat(s) = \begin{cases} \dfrac{s}{\phi_0}, & |s| \le \phi_0 \\ \operatorname{sgn}(s), & |s| > \phi_0 \end{cases} \tag{21}$$

where, s denotes the dynamic sliding manifold defined by (12), ϕ_0 can ensure that the steady-state error is within a small range and avoid chattering.

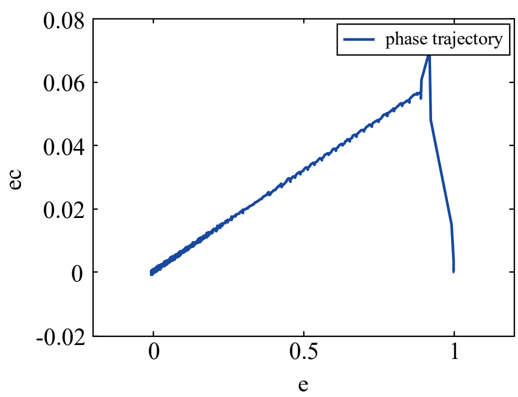

Fig. 6. phase locus

IV. SIMULATION RESULTS

According to the real ship-mounted cranes, the parameters of the system are chosen as: $k_1 = 10$, $k_2 = 2$, $\eta = 0.5$, $\mu = 1$. For the RBF, $c_j = 0.5$, $b_j = 6$. Subsequently, the performance of the modified sliding mode controller is divided into the following two situations for simulation

(1) Case 1：Step response
(2) Case 2：Tracking control of roll motions

The sea state 5 is selected for simulation. Choose the rolling condition of the ship as $\varphi(t) = 12° \cdot sin(0.2\pi t)$. In order to demonstrate the increased performance of the proposed controller versus conventional controller, the simulation results of the conventional SMC and PID controllers are also provided.

4.1 Simulation results of step response

The PID control law is utilized to design the wave compensation system. The controls parameters are well-tuned by trial-and-error method. The simulation results of step response with different control parameters are shown in Fig. 4. The parameters of PID2 are chosen as: $k_p = 450$, $k_i = 120$, $k_d = 80$.

The conventional SMC should be designed based on the accurate dynamic model. We developed the conventional SMC

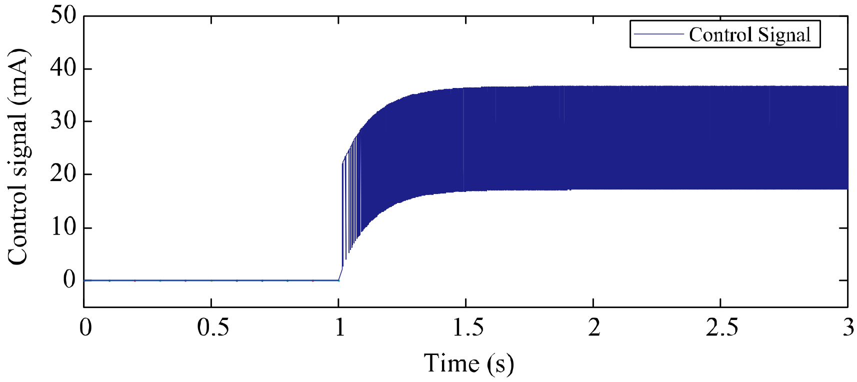

Fig. 7 control signal with SMC (step response)

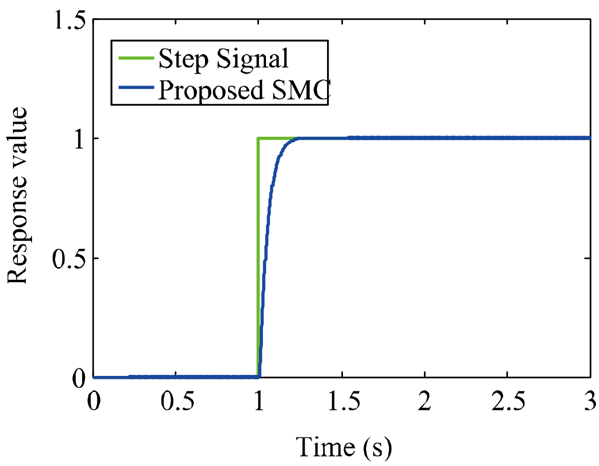

Fig. 8. Step response with proposed controller

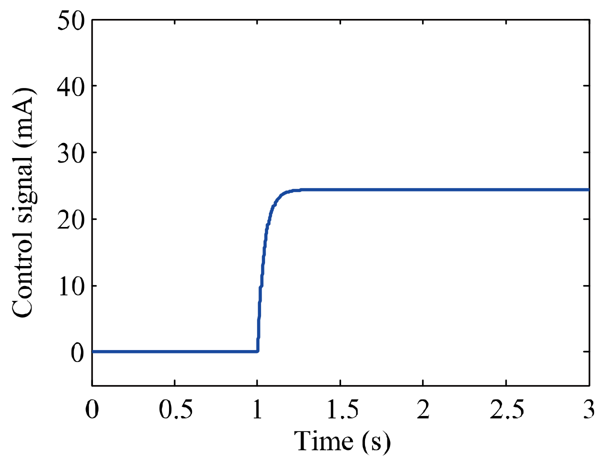

Fig. 9. Control signal with proposed controller

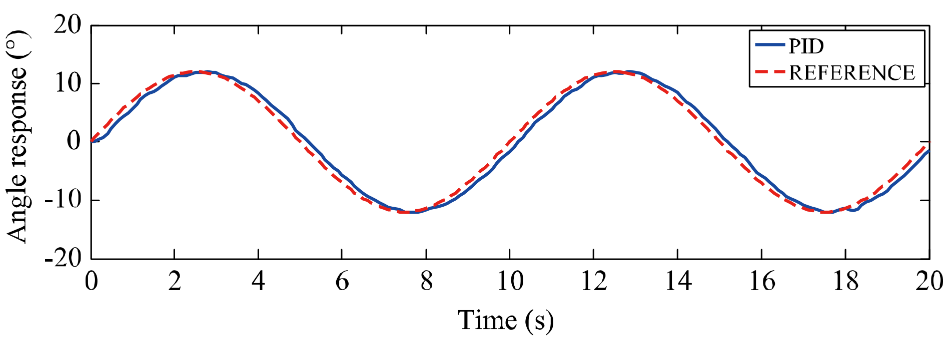

Fig. 10. Tracking control response of wave compensation with well-tuned PID

to compare with the proposed method. The simulation results for step response with conventional SMC controller are shown in Figs.5-7.

The design of conventional SMC is based on accurate mathematical models, but the accurate mathematical models of wave compensation systems are difficult to obtain since the system parameters may be uncertain. The proposed control method can deal with this kind of problem for (19) can estimate the uncertain parameters on-line. The simulation results for step response with proposed RBF SMC controller are shown in Figs.8-9.

According to the Figs. 4-9, we can evaluate the control performance of the proposed RBF SMC controller with PID controller and conventional SMC. Compared the Fig. 4 with Fig. 5 and Fig. 8, for the well-tuned PID2, overshoot = 0.2%, settling time = 1.2 second and steady state error is 0.09. For the SMC controller, settling time = 0.5s with chattering phenomenon in the control signal. For the proposed controller, settling

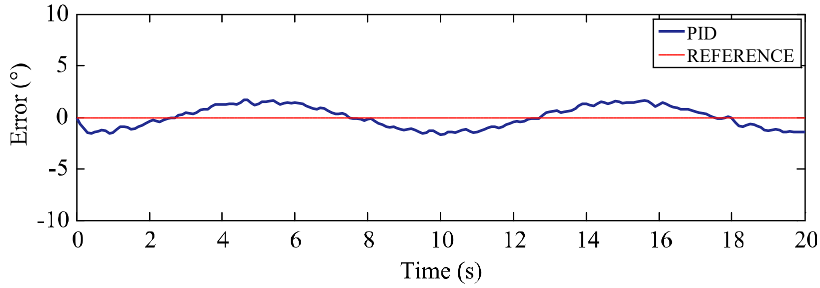

Fig. 11. Tracking error with well-tuned PID

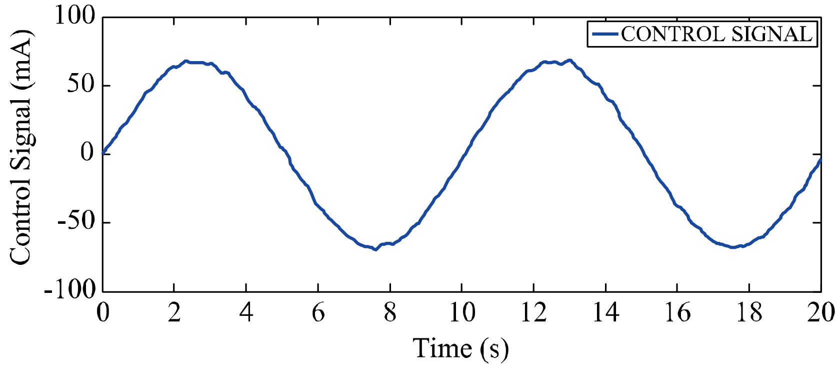

Fig. 12. Control signal with well-tuned PID

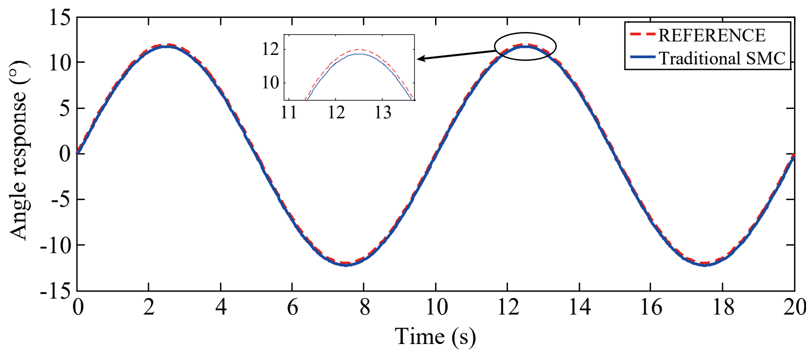

Fig. 13. Tracking control response of wave compensation with SMC

time = 0.3s with no overshoot, no steady state error and no chattering phenomenon in the control signal.

4.2 Simulation results of tracking control of roll motions

The simulation results of tracking control of wave compensation with PID2 are provided in Figs.10-12.

We can learn from Figs.10-12 that the conventional PID cannot eliminate the tracking error absolutely. As shown in Fig.11, there is time-delay phenomenon in the wave compensation system with PID. Fig. 12 shows the control signal has no chattering.

The simulation results of tracking control of wave compensation with conventional SMC are shown in Figs.13-14.

According to the Figs.10-14, the control effect of SMC is better than PID. However, Fig. 14 shows that the chattering phenomenon exists in the control signal, which will bring mechanical wear to the actuator and restrict the application of sliding mode control in the wave compensation practice. Moreover, the SMC needs the system parameters are precisely known.

The simulation results of tracking control of wave compensation with proposed control method for parameters uncertain system are shown in Figs.15-17.

Since the uncertain parameters $\theta f(x)$ and $\beta g(x)$ can be approximated based on (19), we can find the tracking error of the proposed controller can be eliminate effectively without chattering phenomenon in control signal.

According to the Figs. 4-17, we can evaluate the proposed

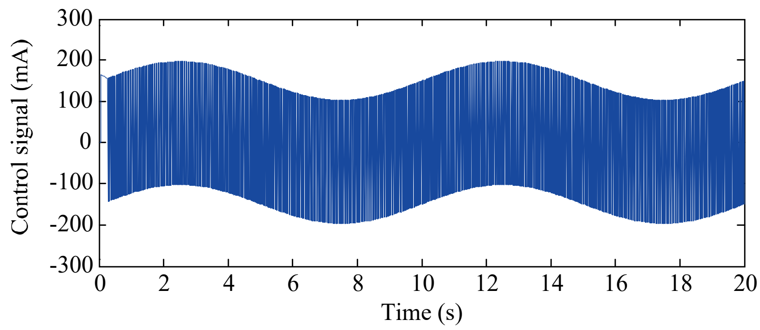

Fig. 14. control signal with SMC (wave compensation)

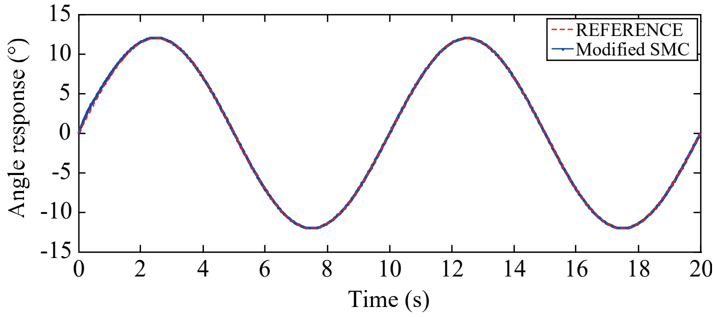

Fig. 15. Tracking control response of wave compensation with proposed controller with uncertain parameter

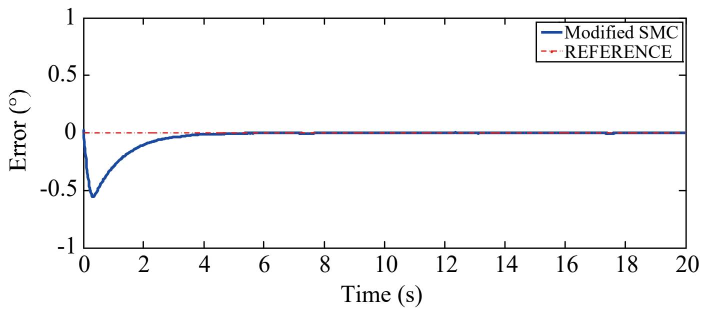

Fig. 16. Tracking error with proposed controller with uncertain parameter

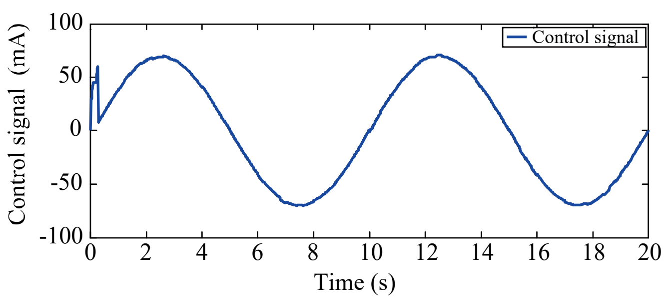

Fig. 17. Control signal with proposed controller with uncertain parameter

controller synthetically. From the Figs. 15-17, the proposed controller can compensate the wave disturbance in time and the tracking error can converge to zero even the system parameters are uncertain. The proposed controller can reduce the chattering phenomenon effectively with better compensation effect. The proposed control method can meet the requirement of the control goal satisfactorily. To some extent, these simulation results demonstrate that the proposed controller is more

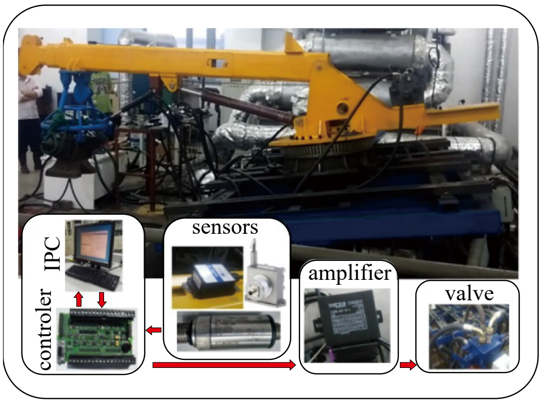

Fig. 18. Hardware experimental setup of ship-mounted crane on the roll motions platform

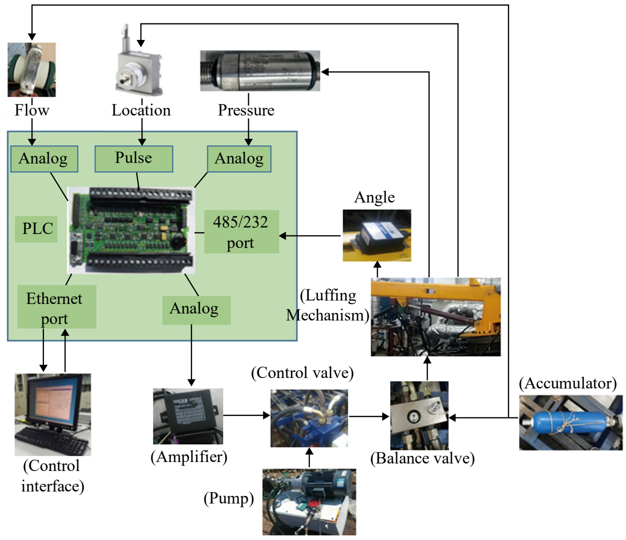

Fig. 19. Hydraulic and acquisition system

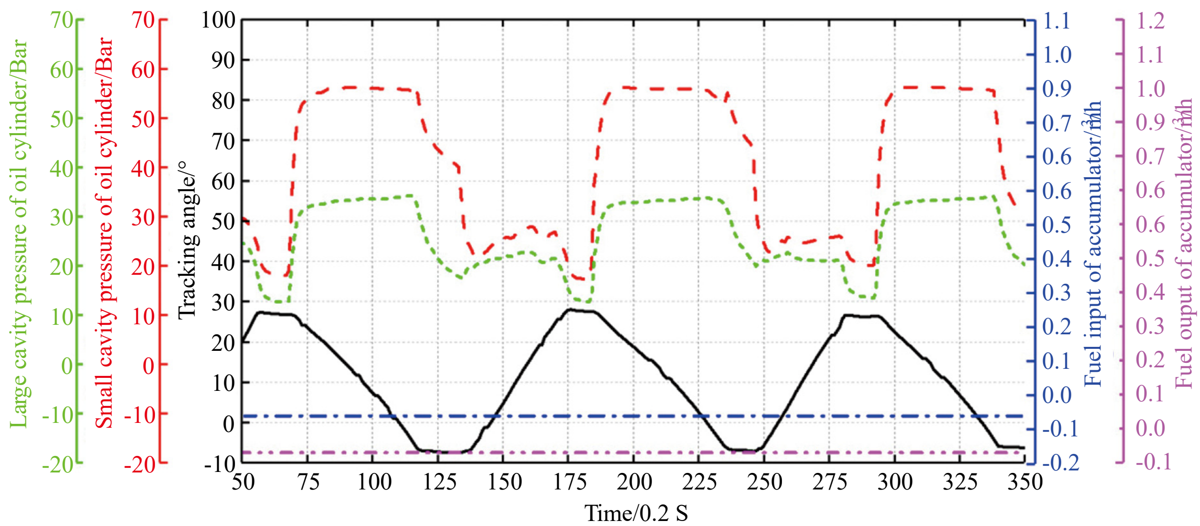

Fig. 20. Experimental results with proposed controller of step response

robust in the wave compensation process when external disturbances and parameter perturbations occur in the ship-mounted crane system.

V. HARDWARE EXPERIMENTS

The hardware experimental setup of ship-mounted crane on the roll motions platform is shown in Fig. 18, which includes a luffing cylinder mechanism to compensate for the swaying of ship hull in Z direction. The rolling motion platform simulates the rolling of ship motion, and simulates the motion of different sea conditions by setting the inclination angle and frequency.

The counter of Siemens S7-1200 controller can collect the pulse of the cylinder's expansion length and the analog function is utilized to collect the pressure of the cylinder's cavity and chamber. The 485 serial port is used to collect the angle of the manipulator. The analog value of the controller outputs 4-20mA current. The amplified current after the proportional amplifier controls the electro-hydraulic proportional directional valve, as shown in Fig. 19.

After simulation tests, much effort have been put to perform experiments to further evaluate the performance of the proposed controller for tracking performance, anti-disturbance ability and dynamic performance under roll motions disturbance. The parameters of the proposed controller are chosen as: $k_1 = 10$, $k_2 = 2$, $\eta = 0.5$, $\mu = 1$. For the RBF, $c_j = 0.5$, $b_j = 6$.

The experimental results of the proposed controller with uncertain parameter for step response are provided in Fig. 20.

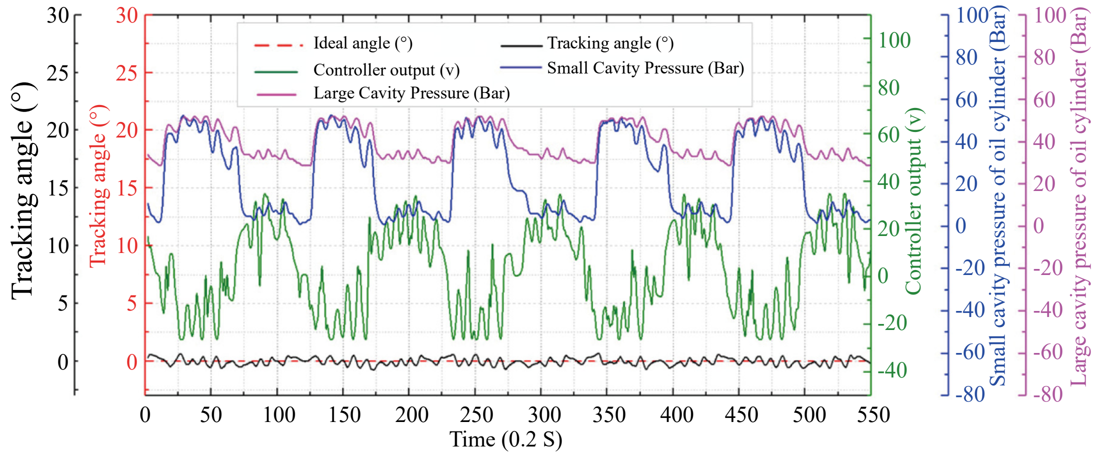

Fig. 21. Experimental results of wave compensation under 6-level sea condition

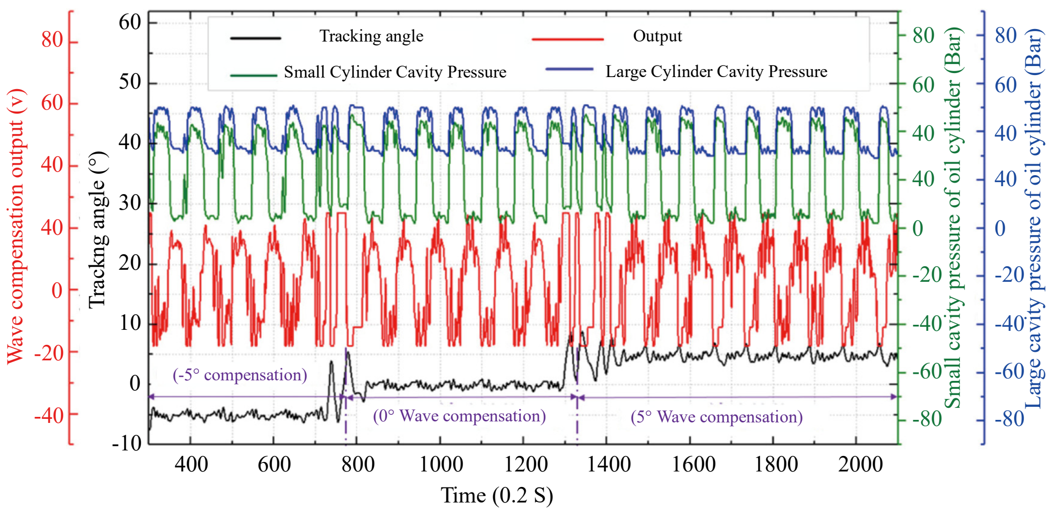

Fig. 22. Experimental results of wave compensation with different desired tracking angle

Fig. 20 shows the collected data of ship-mounted crane on the roll motions platform under the step signal. The step signal is an intermittent periodic signal.

Set the desired tracking angle of the ship-borne the manipulator to be 0°. The wave compensation experiment is carried out under 6-level sea condition and the experimental results can be seen in the Fig. 21.

Besides the desired tracking angle of 0°, the reference angle of the ship-borne the manipulator can be various. The wave compensation experiments are carried out under 3-level sea condition of reference angle to be -5°, 0°, 5° and the experimental results can be seen in the Fig. 22.

By working with the proposed controller, the amplitude of ship-borne the manipulator of the ship-mounted crane can be controlled within 1.5° after wave compensation. The pressure of the cylinder varies steadily, and the distribution is more than 40 Bar. Robust tracking control method of the manipulator can achieve superior control performance on the premise of smooth control inputs, and has satisfactory robustness with persistent disturbances of roll motions and parametric uncertainties.

CONCLUSIONS

In the process of the valve-controlled cylinder of the ship-borne manipulator with the wave compensation system, in order to deal with the persistent roll motions and parametric uncertainties, an improved sliding mode controller with RBF which can realize fast and accurate keep the manipulator angle and resist the wave disturbance effectively is proposed. By using the proposed method, the uncertain parameters of the wave compensation system can be approximate on-line accurate mathematical models are not required. According to the simulations, there are overshoot = 0.2%, settling time = 1.2 second and steady state error = 0.09 for the well-tuned PID controller; for the conventional SMC controller, the chattering phenomenon is not eliminated thoroughly while the proposed controller can basically eliminate the chattering phenomenon in sliding mode control with better compensation effect and enhance the robustness of the control system. According to the experimental results, the proposed method the inclination angle can be reduced significantly within 1.5° in harsh sea conditions and can tracking various desired angle effectively. In conclusion, the proposed control law can improve the stability performance of the ship-borne manipulator effectively under the action of wave-induced roll motions and parametric uncertainties, and enhance the operational ability and safety of the ship-mounted cranes in the marine environment. Our future works will focus on the application of the proposed control law to the real ship-mounted cranes with wave compensation systems.

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REFERENCES

Chen, H. and N. Sun (2020). Nonlinear control of underactuated systems subject to both actuated and unactuated state constraints with experimental verification. IEEE Transactions on Industrial Electronics 67(9), 7702-7714.

Chen, H., B. Xuan, P. Yang and H. Chen (2019). A new overhead crane emergency braking method with theoretical analysis and experimental verification. Nonlinear Dynamics 98(3), 2211–2225.

Do, K. D. and J. Pan (2008). Nonlinear control of an active heave compensation system. Ocean Engineering 35(5-6), 558-571.

Kilic, E., M. Dolen, A. B. Koku, H. Caliskan and T. Balkan (2012). Accurate pressure prediction of a servo-valve controlled hydraulic system. Mechatronics 22(7), 997-1014.

Kim, G. H. and K. S. Hong (2019). Adaptive sliding mode control of an offshore container crane with unknown disturbances. IEEE/ASME Transactions on Mechatronics 24(6), 2850-2861.

Kuechler, S., T. Mahl, J. Neupert, K. Schneider and O. Sawodny (2011). Active control for an offshore crane using prediction of the vessel's motion. IEEE/ASME Transactions on Mechatronics 16, 297-309.

Landet, I. S., A. Pavlov, O. M. Aamo and H. Mahdianfar (2012). Control of heave-induced pressure fluctuations in managed pressure drilling. IEEE Transactions on Control Systems Technology 21(4), 2270-2275.

Li, S., J. Li, Y. Tang, Y. Shi and W. Cao (2019). Model-based model predictive control for a direct-driven permanent magnet synchronous generator with internal and external disturbances. Transactions of the Institute of Measurement and Control 42(3), 586-597.

Linjama, M, M. Huova and K. Huhtala (2016). Model-based force and position tracking control of an asymmetric cylinder with a digital hydraulic valve. International Journal of Fluid Power, 1-10.

Messineo, S. and A. Serrani (2009). Offshore crane control based on adaptive external models. Automatica, 45(11), 2546-2556.

Persaud R, H. Li and J. Leng (2019). Numerical simulation of a passive heave compensator for scientific research ships . Journal of Naval Architecture and Marine Engineering 16(1), 45-59.

Qian, Y., Y. Fang and B. Lu (2019). Adaptive robust tracking control for an offshore ship-mounted crane subject to unmatched sea wave disturbances. Mechanical Systems and Signal Processing 114, 556-570.

Rong, B., X. Rui, Kun Lu, L. Tao, G. Wang and F. Yang (2019). Dynamics analysis and wave compensation control design of ship's seaborne supply by discrete time transfer matrix method of multibody system. Mechanical Systems and Signal Processing 128, 50-68.

Sun, N., Y. Fang, H. Chen, Y. Fu and B. Lu (2018). Nonlinear stabilizing control for ship-mounted cranes with ship roll and heave movements: design, analysis, and experiments. IEEE Transactions on Systems, Man, and Cybernetics: Systems 48, 1781-1793.

Sun, N., Y. Fu, T. Yang, J. Zhang, Y. Fang and X. Xin (2020). Nonlinear motion control of complicated dual rotary crane systems without velocity feedback: Design, analysis, and hardware experiments. IEEE Transactions on Automation Science and Engineering 17(2), 1017-1029.

Sun, W., S.-F. Su, J. Xia and Y. Wu (2020). Adaptive tracking control of wheeled inverted pendulums with periodic disturbances. IEEE Transactions on Cybernetics 50(5), 1867-1876.

Sun, Y., Haiyan Qiang, J. Xu and D. Dong (2017). The nonlinear dynamics and anti-sway tracking control for offshore container crane on a mobile harbor. Journal of Marine Science and Technology 25, 656-665.

Sun, Y., J. Xu, H Qiang and G. Lin (2019). Adaptive neural-fuzzy robust position control scheme for maglev train systems with experimental verification. IEEE Transactions on Industrial Electronics 66(11), 8589-8599.

Sun, Y., W. Li, D. Dong, X. Mei and H. Qiang (2015). Dynamics analysis and active control of a floating crane. Tehnicki Vjesnik 22(6), 1383-1391.

Tuan, L. A., Q. Ha and P. V. Trieu (2019). Observer-based nonlinear robust control of floating container cranes subject to output hysteresis. Journal of Dynamic System, Measurement, and Control 141(11), 111002.

Tuan, L. A., S.-G. Lee, L. C. Nho and H. M. Cuong (2015). Robust controls for ship-mounted container cranes with viscoelastic foundation and flexible hoisting cable. Proceeding of the Institution of Mechanical Engineers part I-Journal of Systems and Control Engineering 229(7), 662-674.

Vaerno, S. A, A. H. Brodtkorb and R. Skjetne (2019). Compensation of bias loads in dynamic positioning of marine surface vessels. Ocean Engineering 178, 484-492.

Wang, X., M. Reitz and E. E. Yaz (2018). Field oriented sliding mode control of surface-mounted permanent magnet ac motors: theory and applications to electrified vehicles. IEEE Transactions on Vehicular Technology, 67(11), 10343-10356.

Wang, Y., B. Jiang, Z. Wu, S. Xie and Y. Peng (2020). Adaptive sliding mode fault-tolerant fuzzy tracking control with application to unmanned marine vehicles. IEEE Transactions on Systems Man, and Cybernetics: Systems, to be published, Doi: 10.1109/TSMC.2020.2964808, 2020.

Woodacre, J. K., R. J. Bauer and R. A. Irani (2015). A review of vertical motion heave compensation systems. Ocean Engineering 104, 140-154.

Yu, H., Y. Chen, W. Shi, Y. Xiong and J. Wei (2019). State constrained variable structure control for active heave compensators. IEEE Access 7, 54770-54779.

Zhang, M. and X. Jing (2020). A bioinspired dynamics-based adaptive fuzzy SMC method for half-car active suspension systems with input dead zones and saturations, IEEE Transactions on Cybernetics, in press, DOI: 10.1109/TCYB.2020.2972322.