

Active Stabilization for Surge Motion of Moored Vessel in Irregular Head Waves

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불규칙 선수파랑 중 계류된 선박의 전후동요 제어

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Abstract : This study was focused on the stabilization of surge motions of a moored vessel under irregular head seas. A two-point moored vessel shows strong non-linearity even in regular sea, owing to its inherent non-linear restoring force. A long-crested irregular wave is subjected to the vessel system, resulting in more complex nonlinear behavior of the displacement and velocities than in the case of regular waves. Sliding mode control (SMC) is implemented in the moored vessel to control both surge displacement and surge velocity. The SMC can provide a closed-loop system with performance and robustness against parameter uncertainties and disturbances; however, chattering is the main drawback for implementing SMC. The goal of minimizing the chattering and state convergence with accuracy is achieved using a quasi-sliding mode that approximates the discontinuous function via a continuous sigmoid function. Numerical simulations were conducted to validate the effectiveness of the proposed control algorithm.

Key Words : Two-point moored vessel, Irregular head waves, Surge oscillation, Quasi-sliding mode control, Sigmoid function, External disturbances

요 약 : 본 논문에서는 불규칙 선수파랑 조건에서 선박계류시스템의 전후동요를 억제하는 연구를 수행하였다. 두점식 계류시스템은 비선형복원력의 특성으로 인하여 규칙파 조건에서도 강한 비선형 응답 특성을 보인다. 종방향 불규칙 장파가 외란으로 선박계류시스템에 작용하게 되면 규칙파 외력이 입사하는 경우보다 변위와 속도에서 더욱 복잡한 비선형 거동이 발생한다. 계의 종동요 변위와 속도를 동시에 억제하기 위하여 슬라이딩모드 제어법(SMC)을 적용하였다. SMC는 매개변수의 불확실성 및 외란에 대한 강인성을 갖는 페루프 시스템을 제공하지만, 채터링은 이 제어법을 사용할 때 큰 단점이 된다. 본 연구에서는 준 슬라이딩모드의 시그모이드 함수를 이용하여 불규칙 해양파의 외란 조건에서 채터링을 줄이고, 수렴의 정확성에 도달하는 목표를 달성하였다. 제어법의 유효성은 수치시뮬레이션을 통해 증명하였다.

핵심용어 : 두점식 계류선박, 불규칙 선수파, 전후동요, 준 슬라이딩모드 제어, 시그모이드 함수, 외란

1. Introduction

For the maritime safety, marine vessels in the ocean waves should be controlled even in the harsh circumstances. The dynamical responses of the vessel system are varied according to the operating conditions of exciting ocean waves. In order to obtain a comfortable working environment, the ship should be

suppressed with an appropriate control method. The various vessel systems contain the inherent strong non-linearity of both two-point moored system (Lee and You, 2018a; Lee and You, 2018c) and rolling vessel system (Lee and You, 2018b; Lee et al., 2020).

Moored vessel can mainly be implemented as a multi-point and a single-point mooring system. These mooring systems represent complex dynamical behavior including co-existing periodic (harmonic as well as sub-harmonic oscillation) and aperiodic (quasi-periodic and chaotic) motions (Gottlieb and Yim, 1992) due

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to nonlinear features of restoring force (Umar et al., 2010). Also, the stability of the moored vessel is governed by strong sensitivity to initial conditions (Ellermann, 2005; Banik and Datta, 2010). Even in case that the harmonic excitation is acting on the system, a two-point moored vessel represents various nonlinear motions such as chaotic motion and limit cycles due to the effect of the strong restoring term (Lee and You, 2018a). Thus, the two-point moored vessel actually resembles the duffing oscillator.

The nonlinear duffing oscillator can be seen as a two-point moored vessel subjected to harmonic excitations. It represents the harmonic or sub-harmonic to chaotic motion (Ellermann, 2005). Duffing type motion has been restrained using several control mechanism such as PID-based controller (Loria et al., 1998), sliding mode controller (Kuo et al., 2008), modified super-twisting algorithm (Khadra, 2016), super-twisting control algorithm (Lee and You, 2018c) and time-delay state feedback (Mitra et al., 2017). Their reports show the mitigation of chattering which is actually undesirable oscillations with finite amplitude with frequency.

The sliding mode control (SMC) is one of the effective control mechanisms for nonlinear dynamical systems ensuring performance and robustness against parameter uncertainties and exogenous disturbances. Sliding surface and active controller are designed to stay the state trajectories on the time-varying sliding surface in finite time. However, one major drawback of SMC is the chattering phenomenon, which results in the harmful failure of actuators with fatigue loads due to the high frequency of switching actions. These inherent problems of chattering in SMC can be improved by suitable measures such as a sigmoid function or the second-order sliding mode. It is difficult to eliminate totally the chattering in second-order sliding mode because it contains the signum function multiplied by some bounds of uncertainties in advance (Edwards and Shtessel, 2016). Despite shortcomings of chattering, SMC has been prominently appeared in the stage of engineering fields due to its strengths of invariability to external disturbances. Recently, higher-order SMC such as super-twisting and adaptive super-twisting algorithm (Xu et al., 2020) have been reported in controlling marine vessel system (Lee and You, 2018c; Lee et al., 2019; Lee et al., 2020). However, since there are many parameters in higher-order SMC, it requires much effort and time to apply in practical cases such as complicated ship models and irregular head waves.

This paper investigates the active stabilization of irregular surge oscillation for a two-point moored vessel under irregular head seas. Surge motions governed by a single-degree-of-freedom (SDOF)

equation. Quasi-SMC is taken into account for ensuring the control performance against uncertainties. The rest of the paper is structured as follows. Section 2 briefly introduces the system dynamics of a two-point moored vessel. In Section 3, Quasi-SMC has been applied to suppress irregular surge oscillation. Section 4 presents numerical simulations for the effectiveness of the proposed control mechanism. Finally, the conclusion will be made in Section 5.

2. Mathematical Formulation

2.1 Two-point Moored Vessel

The two-point moored vessel under irregular head waves governed by SDOF can be simplified by the following nonlinear differential equation (Banik and Datta 2010; Lee and You, 2018a)

$$\ddot{x} + \gamma_1 \dot{x} + R(x) = \bar{F}(\ddot{x}, x, t) / M \quad (1)$$

with

$$R(x) = \Theta [x + \chi_{mr} \operatorname{sgn}(x)] \left\{ \frac{1}{\sqrt{1 + \chi_{mr}^2}} - \frac{1}{\sqrt{1 + [x + \chi_{mr} \operatorname{sgn}(x)]^2}} \right\}$$

$$\gamma_1 = C/M, \quad \Theta = X_s/M, \quad \chi_{mr} = b_1/b_2,$$

$$\operatorname{sgn}(x) = \begin{cases} +1 & \text{for } x > 0 \\ 0 & \text{for } x = 0 \\ -1 & \text{for } x < 0 \end{cases}$$

where $M = m_v + m_a$; m_v denotes the original vessel mass (kg) and m_a is the added mass; C represents the damping coefficient ($N.s/m$); $R(x)$ is the restoring force; \bar{F} represents external excitation force (N); χ_{mr} is the non-dimensional values related to the distance of each moorings; sgn refers to signum function; X_s is the stiffness (N/m) including elastic cable force defined as $X_s = 2E_{cf}\sqrt{b_2^2 + b_1^2}$; E_{cf} is the elastic cable force; b_i ($i = 1, 2$) designates distances between the center of vessel system and each mooring lines; over-dot denotes a derivative of the variable with respect to time; x , \dot{x} and \ddot{x} represent the surge displacements (m), surge velocity (m/s) and surge acceleration (m/s^2), respectively (Banik and Datta 2010; King and Yim, 2007).

The restoring force assumes linear elastic behavior so that the non-linearity is strictly due to the geometric configuration of the system (King and Yim, 2007). Particularly, the restoring force can be approximated by the least square representation as $\sum \Phi_n x^n$, : $n = 1, 3, \dots, N$ where Φ_n describes the exciting frequency. The

governing system non-linearity $N=3$ is mainly cubic term (x^3). Polynomials of various orders are employed within experimental range. In practice, the restoring force $R(x)$ can be expressed as linear and cubic polynomial form as $v_1x + v_2x^3$ (Banik and Datta 2010; Lee and You, 2018a). The nonlinear chaos motion mainly depends on the inherent restoring force term and the initial condition in case of regular excitation. Assuming the vessel mass has just unit mass for simplicity, it can be scaled into the vessel mass or $f_{sea} = \bar{F}/M$ (N/kg). Thus, the two-point moored vessel under irregular head seas can be written as

$$\ddot{x} + \gamma_1 \dot{x} + v_1x + v_2x^3 = f_{sea}(t) \quad (2)$$

2.2 Irregular head waves

The two-point moored vessel shows rich nonlinear dynamical behaviors due to its strong non-linearity even in a regular wave. In this section, we introduces a long-crested irregular sea to show the performance of the proposed control algorithm. A long-crested sea has the unidirectional wave crests with varying separation but remaining parallel to each other (Perez, 2005). When the storm blows for a long time, a fully developed sea is created. Such long waves form a wave spectrum. We employed the Pierson-Moskowitz spectrum (PM spectrum) on the two-point moored vessel as the real sea states. PM spectrum is a one-parameter wave spectral formulation for fully developed wind-generated seas based on the wave spectra information of North Atlantic Ocean as follows (Fossen, 2011)

$$S(\omega) = S_a \omega^{-5} \exp(-S_b \omega^{-4}) \quad (m^2s) \quad (3)$$

with $S_a = 8.1 \times 10^{-3} g^2$ and $S_b = 0.74(g/S_c)^4$, where S_c means the wind speed at the height 19.4 m.

Assuming the waves can be represented by Gaussian random process and $S(\omega)$ is narrow-banded, S_b can be rewritten as $0.0323(g/H_s)^2 = 3.11/H_s^2$ where H_s is the significant wave height. The sea surface elevation of a long-crested irregular sea can be given as the sum of harmonic wave components i as the following equation

$$\xi(t) = \sum_{i=1}^N \bar{W}_i \sin(\omega_i t - \nu_i x + \kappa_i) \quad (4)$$

where \bar{W}_i represent the wave amplitude defined as $\sqrt{2S(\omega_i)\Delta\omega}$; ω_i is the circular frequency; ν_i is the wave number; κ_i is the random phase angle of wave component with uniform distribution in $[0, 2\pi]$. (Perez, 2005; Fossen, 2011).

2.3 Robust control synthesis

By considering the excitation f_{sea} as a time-varying disturbance, the control system represents a forced surge system by adding the actuation input u .

$$\ddot{x} + \gamma_1 \dot{x} + v_1x + v_2x^3 = d + u \quad (5)$$

where d represents the total amounts of disturbances such as waves, wind, currents, and any impacts in longitudinal direction.

An active controller can be designed to achieve the satisfactory anti-surfing effect for marine vessel. For the state variables denoted as $x = x_1$ and $\dot{x} = x_2$, the governing equation can be described as into state-space representation as follows

$$\dot{x} = T_a x + f(x, t) + T_b u + T_c d \quad (6)$$

where state vector, system matrices, and nonlinear term are given by

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad T_a = \begin{bmatrix} 0 & 1 \\ -v_1 - \gamma_1 & 0 \end{bmatrix}, \quad T_b = T_c = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

and $f(x, t) = \begin{bmatrix} 0 \\ -v_2 x_1^3 \end{bmatrix} \quad (7)$

As shown in Fig. 1, the proposed controller is employed to handle the error responses of the two-point moored vessel under irregular head waves.

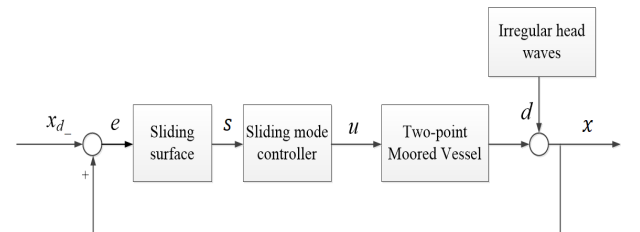


Fig. 1. Block diagram of surge control for a two-point moored vessel under irregular head waves.

By introducing the surge tracking error $e = x_1 - x_d$ between the actual output x_1 and desired value x_d , the variables on the sliding surface are considered as

$$s = \lambda_1 \dot{e} + \lambda_2 e \quad (8)$$

where λ_1 and λ_2 are positive constants which are related to the control accuracy and rate of convergence for the moored vessel. From (6) and (7), the sliding mode dynamics can be derived as

$$\dot{s} = P_0 + \lambda_1 (d + u) \quad (9)$$

where

$$P_0 = \lambda_1 (-\gamma_1 x_2 - v_1 x_1 - v_2 x_1^3 - \ddot{x}_d) + \lambda_2 (x_2 - \dot{x}_d).$$

The control objective is to design a suitable controller to ensure the robust stabilization of sliding mode dynamics asymptotically or $\dot{s} = 0$ under uncertainties. In order to achieve the goal, the active controller is designed with the equivalent part and switching part as follows

$$u = -\frac{P_0}{\lambda_1} + \frac{1}{\lambda_1} u_{sw} \quad (10)$$

where $-\frac{P_0}{\lambda_1}$ and $-\frac{1}{\lambda_1} u_{sw}$ represent the equivalent controller and switching controller, respectively. Thus, the sliding mode dynamics in equation (9) can be rewritten as

$$\dot{s} = \lambda_1 d + u_{sw} \quad (11)$$

In order to solve the chattering phenomenon, Quasi-SMC technique is implemented where the discontinuous term on the controller is replaced by a continuous sigmoid function

$$\text{sign}(s) \approx \frac{s}{|s| + \epsilon} \quad (\text{Shtessel et al., 2014; Cuong et al., 2020}).$$

Assume that the disturbance is bounded by a positive constant ρ , satisfying $|d| \leq \rho$. The switching controller is designed as

$$u_{sw} = -\beta \frac{s}{|s| + \epsilon} - \lambda_1 \rho \quad (12)$$

where β is a sufficiently large positive constant, and ϵ is a free parameter which can be chosen arbitrarily by the system designer.

Theorem 1. The surge displacement x_1 of the moored vessel (6) are regular to track the constant reference signal x_d asymptotically as $t \rightarrow \infty$ for all initial $x_1(0)$ with the sliding surface (8) and the sliding mode control law (10) and (12), where β, λ are positive constants.

Proof: To prove the closed-loop stability, the quadratic Lyapunov function candidate is considered as follow.

$$V(s) = \frac{1}{2} s^2 \quad (13)$$

The time-derivative of V is obtained as

$$\dot{V} = s \dot{s} \quad (14)$$

Substituting (11) into (14) leads to the following relation

$$\dot{V} = s (\lambda_1 d + u_{sw}) \quad (15)$$

From (12) and (15), one yields,

$$\begin{aligned} \dot{V} &= s (\lambda_1 d - \beta \frac{s}{|s| + \epsilon} - \lambda_1 \rho) \\ &\leq \lambda_1 |s| (|d| - \rho) - \beta \frac{s^2}{|s| + \epsilon} \end{aligned} \quad (16)$$

Since β, λ_1 and ρ are positive, it is obvious that \dot{V} is a negative definite function, i.e., $\dot{V} \leq 0$. Thus, the time convergence of tracking error $\lim_{t \rightarrow \infty} \|e(t)\| = 0$ is guaranteed by Lyapunov's stability theory. This completes the proof.

3. Simulation tests

Recent developments in sliding mode controls have been chosen to stabilize the surge oscillation of a two-point moored vessel subjected to the irregular head waves. Table 1 shows the main parameters for the moored vessel system (Shah et al., 2005). The dynamical model is a vessel type structure with two mooring lines

in the fore and aft position. When the irregular head waves are excited about this structure in the longitudinal direction, the system exhibits the irregular complex oscillations on the displacement and the velocity. So, the proposed SMC is aiming to solve convergence problems of the two states and chattering reduction within finite time simultaneously.

The simulation results of the controlled moored vessel will be dependent on the control parameters. In the simulation, some parameters for control synthesis are given as $\lambda_1 = 0.1$, $\lambda_2 = 0.04$, $\beta = 30$ and $\epsilon = 0.01$, in which the parameters are determined through many tests. In order to find the optimum parameters, we set the minimum value for reference point. Then, we increase the each parameter gradually. The parameters λ_1 and λ_2 in sliding mode variables affect the convergence rate and the chattering alleviation for surge responses. In addition, the parameters β and ϵ are also set through many trials guaranteeing the chattering mitigation. The initial conditions of the surge dynamics are selected as $[x_0, \dot{x}_0] = [0.5 \text{ (m)}, 0.1 \text{ (m/s)}]$.

Table 1. Model parameters of two-point moored vessel

Parameters	Values
Structure type	Vessel
Mass of moored vessel	$1.2 \times 10^5 \text{ kg}$
Specific gravity of concrete	2.4
Number of anchored mooring lines	2
Total length of each mooring lines	500 m
Young's modulus of mooring lines	$20.595 \times 10^9 \text{ N}\cdot\text{m}^2$
γ_1	0.01 s^{-1}
v_1	0.0213 s^{-2}
v_2	$0.319 \text{ m}^2\text{s}^{-2}$

Fig. 2 shows time history curves for a long-crested irregular sea with significant wave height (H_s) 4.82 m and wind speed 15 m/s. Complex irregular wave elevations can be observed from 0 to 100 seconds. These waves excited on the moored vessel in the longitudinal direction as disturbances. When no control action is employed, the moored vessel shows various irregular motions depending on initial conditions even in regular excitations (Lee and You, 2018a; Lee and You, 2018c).

In this paper, irregular head waves have been introduced such as PM spectrum for a real cases. The moored vessel is still in a state of nonlinear surge oscillations with irregular excitations. An

active controller has been initiated to suppress the irregular oscillations of two-point moored vessel due to the head seas at 2000 seconds.

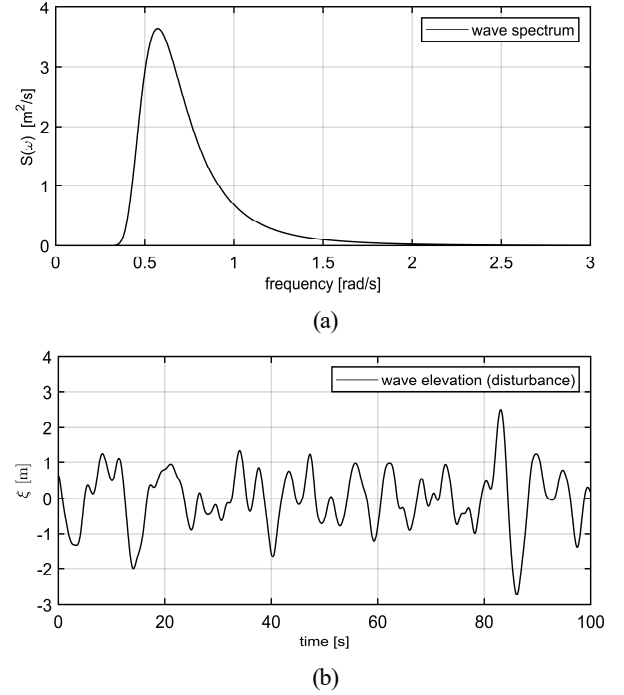


Fig. 2. Time history curves for a long-crested irregular sea: (a) PM spectrum (b) wave elevation.

In order to compare the effectiveness of active control input, the uncontrolled case and controlled case are compared in Figs. 3 and 5. In addition, Figs. 3 and 4 depict the responses of surge displacement and its error, respectively. The surge motion depicts the irregular oscillations and the responses riding the waves before control action due to the effect of strong restoring and the disturbances. It can be observed that the mooring vessel stays on the near zero position with the help of an active controller. Tracking error is a measure of deviation from the benchmark, in which tracking error of surge displacement marked less than 0.5 m under control action. So, the control action achieves the design goal of providing low tracking error even in heavy weather. Simultaneously, as shown in Figs. 5 and 6, the state of surge velocity is effectively suppressed. It is noted that a peak of velocity can be happened when the control action starts. The trade-off is necessary for control performance and control gain. Also, the errors of surge velocity are decreased to near zero under control shown in Fig. 6.

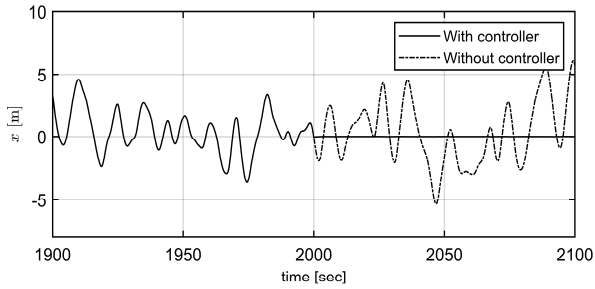
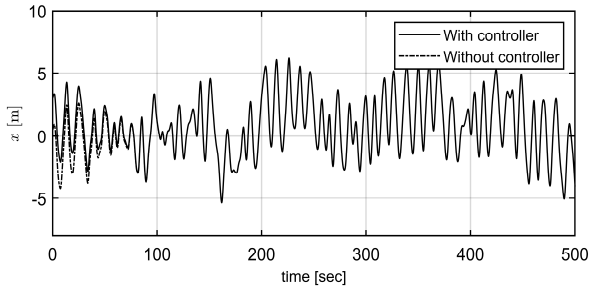


Fig. 3. Comparison of surge suppression with/without controller (control action starts at $t = 2000$ sec).

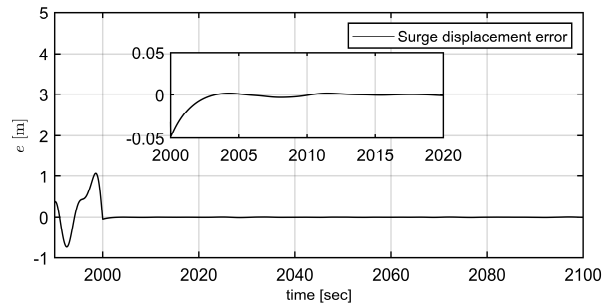


Fig. 4. Error of surge displacement under control action.

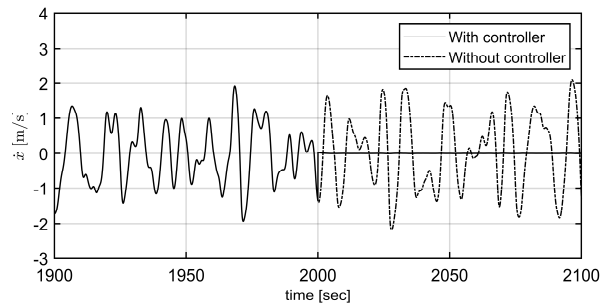


Fig. 5. Comparison of surge rate suppression with/without controller (control action starts at $t = 2000$ sec).

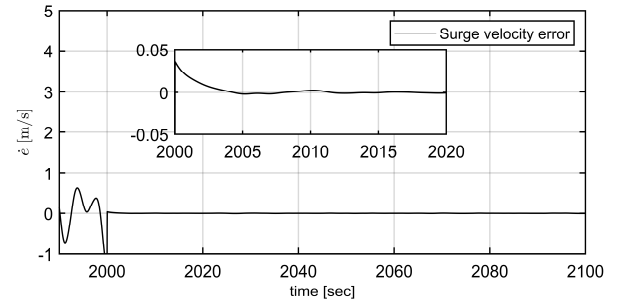


Fig. 6. Error of surge velocity under control action.

Fig. 7 represents the control activity using the proposed quasi-SMC, in which discontinuous high-frequency phenomenon has been significantly reduced under the proposed quasi-SMC. The switching part of the control law in equation (10) helps to drive the state trajectories on the sliding surface regardless of disturbances. Due to the irregular head waves, the harmonic curve can hardly be seen in the control input. Chattering is almost removed with the help of a quasi-SMC which approximates the discontinuous function by a continuous sigmoid function in equation (12). This control law can be applied to some actuators to propel or stop the ship effectively. Since the discontinuous control causes the failure of actuators with fatigue loads, chattering alleviation is important when the SMC is employed to stabilize surge oscillation of the moored vessel. The control action is highly related to the role of the sliding variable in Fig. 8. As described in SMC theory in equations (8) and (9), the sum of position error and velocity error decreases to zero in finite time using the proposed controller.

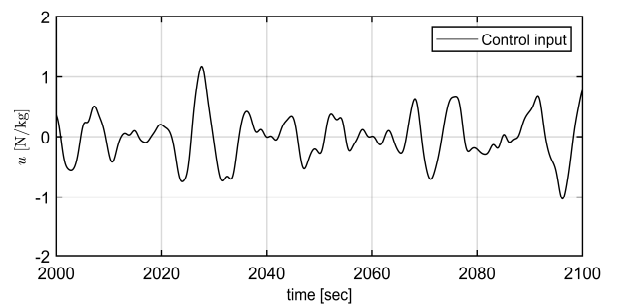


Fig. 7. Control activities against irregular head waves (starting at $t = 2000$ sec).

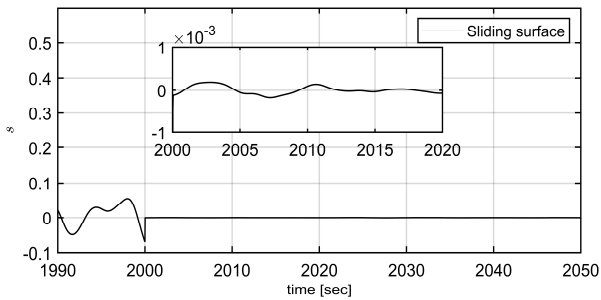


Fig. 8. Time history curve for sliding variable before and after control action.

In previous reports by Lee et al. (2020) and Shtessel et al. (2012), the approach of sigmoid function is vulnerable to the high disturbances since the s-trajectories are constrained in the vicinity of the sliding surface rather than on the surface. As seen in Figs. 4 and 6, there exist some errors after control action. However, due to its simplicity compared to the control effort, the proposed quasi-SMC can be described as one of the effective mechanisms with respect to suppression of the two-point moored vessel under irregular head waves such as a long-crested irregular sea.

4. Conclusions

The quasi-SMC scheme has been presented for suppressing the complex surge oscillations of a two-point moored vessel under irregular head waves such as a long-crested sea. Due to the inherent characteristics of restoring forces, it is hard to expect the moored vessel to ensure the comfortable working place until the control action activates. For the purpose of safety on the moored vessel under real sea conditions, one of the effective control schemes is considered.

The proposed nonlinear control system has exhibited the strength of SMC synthesis providing control accuracy, robustness, and simple implementation against disturbances. Simulation results revealed that the state variables of surge displacement and velocity of the two-point moored vessel eventually become near zero with active control action. The chattering of the SMC algorithm has been removed by the implementation of a quasi-sliding mode approximating the sign function by the continuous sigmoid function. Finally, this work has been focusing on controlling surge motions for a simple SDOF moored vessel under irregular head waves and uncertainty.

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