In this note, a novel multitechnique concise robust control scheme, based on the mirror mapping technique (MMT), closed-loop gain shaping algorithm (CGSA), Smith predictor (SP), and nonlinear feedback technique (NFT), is proposed for the pressure control of the liquefied natural gas (LNG) carrier insulation containment space. Firstly, a kind of integral unstable time-delay model is obtained by linearizing the nonlinear model of the pressure maintenance system around its equilibrium. By using the MMT and CGSA, one acquires the corresponding stable mirror mapping model of the unstable linear model and the designed controller. And the SP is introduced to tackle the time-delay problem. In addition, for the purpose of energy saving, the NFT is added into the control scheme. Finally, a set of experiments has been employed to illustrate the control effects, and the results show that it can achieve satisfying performance in aspects of disturbance rejection and energy saving.

1. Introduction

According to the statistical report of BP p.l.c. [1], natural gas consumption rose by 96 billion cubic meters (bcm), or 3%, the fastest since 2010, as well as gas trade expanded by 63 bcm, or 6.2%, with growth in LNG (liquefied natural gas) outpacing growth in pipeline trade in 2017. In addition, because the LNG can be compressed into a 1/600 volume of its vapour phase at cryogenic temperature, transporting or storing LNG by the LNG carrier is widely employed [2]. Therefore, the demand for LNG carriers is correspondingly growing, and its safety and security should be paid more attention.

In a general way, LNG carriers are mainly divided into two types: Moss-type and membrane-type carrier. Currently, more than half the LNG carriers employ the membrane-type CCSs (cargo containment systems), which are further divided as NO 96 system and Mark III system as shown in Figure 1, both of which are developed by GTT (Gaztransport and Technigaz, France) [3]. The CCSs are composed of two different types of barriers, primary barrier and secondary barrier, to prevent heat transfer and LNG leakage. For these purposes, many insulation materials such as perlite, plywood, and polyurethane foam are employed to build the insulation containment space. Besides, nitrogen will be filled into the space to prevent heat exchange, as well as to detect the leakage easily and avoid producing the combustible mixture when the leakage occurs. Because of the importance of the CCSs, there have been many pieces of research for CCSs, especially the membrane-type CCSs. They investigated the strength and fatigue performance of the insulation system [2, 4, 5], cryogenic reliability of the insulation system [3, 6, 7], the structure design of the barriers [8, 9], and so forth. However, owing to the business reasons, there was little literature related to the pressure maintenance system of CCSs’ insulation containment space.

As mentioned above, the insulation containment space will be filled with nitrogen not only to keep its inert state but also to maintain a certain pressure difference between the primary barrier and the secondary barrier [10]. On account of the sloshing of the liquid tanks and adjustment of the valves, the pressure of the insulation containment space will be occasionally changed which will result in refilling or outdrawing nitrogen to keep the pressure difference. Hence, to develop a concise robust controller for the insulation containment space pressure control of the LNG carrier with...
the disturbances is the goal of this paper. Previous studies [11, 12] have shown that the pressure control of the insulation containment space is characterized by nonlinear, unstable, significant time delay, and complex. Considering the characteristics of the control system and the compatibility of the control algorithm, mirror mapping technique (MMT), closed-loop gain shaping algorithm (CGSA), and Smith predictor (SP) are introduced to develop a controller for the system in this note. Furthermore, for the purpose of energy saving, a novel technique—nonlinear feedback technique (NFT)—is employed to enhance the performance of the control scheme. The simulation results show that the multitechnique concise robust control scheme based on the aforementioned techniques and algorithms has strong robustness and economy. The main contribution and key features of our work can be summarized as follows: a novel concise robust control scheme by the multitechnique is proposed for the insulation containment space pressure control of the LNG carrier. Compared with the existed studies, the proposed scheme is with concise form and parameter tuning procedure which lead to ease implementation in practice and more flexible in dealing with unstable systems with time delay.

The remaining part of the paper is organized as follows. Section 2 introduces the mathematic model and control methods, while the control laws are presented in Section 3. Simulation results are illustrated and discussed in Section 4, and conclusions are drawn in Section 5.

2. Mathematic Model and Control Methods

2.1. Mathematic of the Control Plant. This note concentrates on the pressure maintenance problem of the insulation containment space of membrane-type LNG carriers. Figure 2 shows the schematic diagram of the LNG carrier CCS’s pressure maintenance system. Valve 1 is a pressure control valve, which controls the pressure difference between the primary insulation space and the secondary isolation space by injecting nitrogen. Valve 2 is the nitrogen supply valve. Valve 3 and valve 4 are the pressure control valves for the primary insulation space and the secondary insulation space, respectively, which both connect to the vent mast and will release excess nitrogen to the atmosphere through the vent mast when the isolation valve is opened. Valve 5 is a connection valve. In addition, safety valves 1 and 2 are designed for an emergency case, when the inner pressure exceeds the atmospheric pressure, the safety valve will be opened. Note: the injection and outflow of nitrogen are controlled by different valves, and the designed controller can only control valve 1.

In order to ensure the safety of cargo handling, the pressure of the primary insulation space and the secondary insulation space should be kept in 0.4–0.6 kPa and 0.2–0.4 kPa, respectively, keeping a pressure difference (0.2 kPa) between the two spaces not only to protect the primary barrier and secondary barrier but also to keep the shape of the cargo tank [10]. Based on [12], a nonlinear model of the system relating to the pressure difference $P_e$...
between the two insulation spaces and the flow rate \( u_n \) of the nitrogen gas is formulated as

\[
\rho_{N_2} g^\hat{P}_c = F_e - \kappa \frac{u_n^2}{P_e^2}
\]

where \( \rho_{N_2} \) (in kg/m³) is the density of supplied nitrogen, \( g \) is the gravitational acceleration, \( F_e \) is the damping force due to the nonideal condition, and \( \kappa \) is a constant depending on the material parameters. For analysis and control design purposes, the nonlinear model should be linearized around an equilibrium point \( P_{e0} = 5.0 \) mbar, \( u_0 = 42 \) m³/h. By referring to parameters of the physical system [12], the overall plant transfer function is derived as

\[
G(s) = \frac{\Delta P_x(s)}{\Delta u_x(s)} = \frac{3.25}{s(s - 0.78)} e^{-0.25s}.
\]

2.2. MMT and CGSA. The MMT was firstly introduced by Zhang and Jia [13] in 2000, who developed it as a method for controlling the unstable systems. After that, this technique was further applied to symmetric pole-zero cases and time-delay systems, as well as its application scenarios and general implementation procedure were summarized for easy use [14–16]. Through these years of continuous development, it has gradually become a mature technology for the control of an unstable system.

**Definition 1.** For an unstable process, the symmetric values of zeros (or poles) in the open right half plane are referred as their mirror images.

**Definition 2.** By replacing zeros (or poles) in the open right half plane with their mirror images, the mirror mapping process of the unstable plant is constructed, which is a minimum-phase system.

It is obvious that equation (2) shows a kind of unstable system with time delay, \( s = 0.78 \) which is its unstable pole and \( s = -0.78 \) is its mirror-image pole. After the mirror mapping process, the transfer function of the system can be described as

\[
G'(s) = G_1(s) \cdot G_2(s) = \frac{3.25}{s(s + 0.78)} e^{-0.25s},
\]

where \( G_1(s) = 3.25/s(s + 0.78) \), \( G_2(s) = e^{-0.25s} \) is a pure time delay.

Figures 3 and 4 present the comparison of the root locus diagram and Bode diagram of \( G_1 \) before and after mirror mapping, respectively. It is obvious to note that, after the mirror mapping process, the system becomes stable and the phase-frequency characteristic is much improved.

The CGSA [17] is a simplified H∞ mixed sensitivity algorithm by directly shaping the singular value curves of \( S(s) \) (the sensitivity function) and \( T(s) \) (the complementary sensitivity function), and there exists correlativity \( T(s) = I - S(s) \). The complementary sensitivity function \( T(s) \) of a typical control system has low-pass characteristics to guarantee the robust performance, and the largest singular value equals to unit one to follow the reference signal without the tracking error. The high-frequency asymptote slope of \( T(s) \) determines how much the system is sensitive to the invalid disturbance frequency and is usually suggested to be 20 dB/dec, 40 dB/dec, and 60 dB/dec. That generates the common shaping selection \( T(s) = 1/(T_0 s + 1)^i \) for \( i = 1, 2, \) and 3, respectively, which are corresponding to the 1st, 2nd, and 3rd order CGSA. Equation (4) presents the formulation of the CGSA:

\[
T(s) = \frac{1}{(T_0 s + 1)^i} = K(s)G(s).
\]

where \( G(s) \) is the stable control plant, \( K(s) \) is the controller, \( T_0 \) is the tuning parameter, and the inverse \( 1/T_0 \) is just the frequency bandwidth of \( T(s) \). In brief, according to the shape of the singular value curve of the robust performance index, a robust controller can be directly constructed by using four parameters having engineering significance of the closed-loop transfer function: the largest singular value, bandwidth frequency, peak value, and slope of high-frequency asymptote.

To further improve the control effect of the CGSA, Guan et al. [18] gave a method to eliminate static errors by increasing a minor integral term. Furthermore, Zhang and Guan [19, 20] proposed an approach to improve response speed when using CGSA, which was, adding constant at the proportional term of the PID controller got through Zhang’s model. And the improved CGSA is employed in this note.

2.3. SP and NFT. The SP is a widely used time-delay compensation scheme by introducing a compensator in parallel with the controlled object to weaken and eliminate the time delay. Since it was proposed by O. J. M. Smith in 1957, there has been numerous theoretical analyses and experimental applications in regard to the SP. SP control is a feedback control scheme that has a minor loop as shown in Figure 5 [21]. \( G \) denotes a stable control plant without time delay. \( L \) is a positive constant representing pure lag time. \( G' \) and \( L' \) are the nominal version of \( G \) and \( L \), respectively. \( K \) denotes the controller to be designed and constructs the compensator with the minor loop. The main purpose of the minor loop is to eliminate the actual delayed output and to feed the predicted output to \( K \). One can suppose there is no time delay in the control loop when designing controller \( K \). Thus, PID controllers going through Zhang’s model can be successfully applied together with CGSA.

However, the compensation scheme is limited to the integrating unstable process. It is very fragile to the modeling mismatch error and the unstable dynamic. Motivated by the observation, lots of modified SPs have been developed [22–24]. Other than the SP, there are other methods used to cope with the time delay. The time delay is usually deemed as a model perturbation, taking advantage of the robustness of the controller, and its impact can be largely ignored or approximated [25]. And the Padé approximation is one of the approximation methods applied to replace the time delay [26]. Combining the pressure containment problems, the SP
is chosen preferentially, and the other two methods are employed as the comparison cases in this note.

The NFT is a novel technique used to improve the control performance by employing a nonlinear-driven function of error, between the reference signal and the actual system output, as the input of the control law, which can achieve the same control effect with minor control action under the unchanged control law. In addition, its effectiveness has been validated through the theoretical analysis and the simulation experiments relating to the ship course keeping control. However, the researcher should make prudent use of the NFT when the feedback error is too large, which may cause the instability of the control system [27–29].

The nonlinear feedback system configuration is shown in Figure 6, contrary to the standard feedback configuration. The nonlinear-driven function \( f(\omega_1 (r - y)) \) is introduced in the scheme instead of the conventional feedback error \((r - y)\), where \(\omega_1\) is the dimensionless system frequency; \(K\) is the controller to be designed; and \(G\) is the control plant. Compared to conventional approach \(y = K (r - y)\), under the NFT, \(y = K f(\omega_1 (r - y))\) which changes the feedback error \(e\) from linear to nonlinear by the nonlinear-driven function \(f\), and the control performance change accordingly. In this note, a bipolar sigmoid function is employed as the nonlinear-driven function \(f\), and the experimental results show that the nonlinear feedback driven by bipolar sigmoid function can obtain good performance on the steady state, dynamic performance, and control output, which could result in the energy saving of the closed-loop system on the basis of the unchanged controller \(K\).

### 3. Controller Design

By the meaning of the mirror mapping technique which introduced in Section 2.2, the overall plant transfer function (i.e., equation (2)) is transformed into \(G'(s)\) (i.e., equation (3)). Taking no account of the pure time-delay term \(e^{-0.25s}\) of \(G'(s)\), the 2nd order closed-loop gain shaping algorithm is applied to \(G_1(s)\). In addition, for the purpose of eliminating the static error of the system, a minor constant \(\varepsilon\) (\(\varepsilon < 0.001\)) is added into the denominator of \(G_1(s)\). In addition, its

\[
G'_1(s) = \frac{3.25}{s(s + 0.78)} + \varepsilon
\]
Substituting equation (5) into equation (4) and applying the 2nd order closed-loop gain shaping algorithm (that is, i = 2 in equation (4)), a linear proportional-integral-differential (LPID) plus the first-order filter controller is obtained.

\[
\frac{1}{(T_0s + 1)^2} = \frac{G_1'(s)K(s)}{1 + G_1'(s)K(s)}
\]

\[
K(s) = \frac{1}{G_1'(s)T_0s - (T_0s + 2)}
\]

\[
= \frac{1}{T_0s + 2} \left( \frac{0.78}{3.25T_0\omega + \rho} + \frac{\varepsilon}{3.25T_0\omega + \rho} + \frac{s}{3.25T_0\omega + \rho} \right).
\]

To adjust the rise time of the system, constant ρ is added at the proportion term of equation (6), and the controller is changed into

\[
K_1(s) = \frac{1}{T_0s + 2} \left( \frac{0.78}{3.25T_0\omega + \rho} + \frac{\varepsilon}{3.25T_0\omega + \rho} + \frac{s}{3.25T_0\omega + \rho} \right).
\]

And in order to further enhance the effect of energy saving, \( f(\omega(r - y)) \) is added into the control scheme. A bipolar sigmoid function is chosen as the nonlinear-driven function \( f \), and then one gets the nonlinear feedback \( 1 - e^{-2\omega/1 + e^{-2\omega}} \) for the control system. The controller output \( y \) is given as

\[
y = \frac{1}{T_0s + 2} \left( \frac{0.78}{3.25T_0\omega + \rho} + \frac{\varepsilon}{3.25T_0\omega + \rho} + \frac{s}{3.25T_0\omega + \rho} \right) \left( 1 - e^{-2\omega/1 + e^{-2\omega}} \right).
\]

where \( \omega \) is the gain coefficient of the regulated nonlinear feedback that makes the system energy-efficient, usually it is between 0.1 and 1. \( \varepsilon \) is the feedback error.

For the sake of reducing the impact of pure time delay of the control plant, the SP is applied in this note. Figure 7 shows the configuration of the nonlinear feedback system driven by a bipolar sigmoid function.

4. Simulation Study and Analysis

In the pressure maintenance system of the LNG carrier CCS, the disturbance is mainly from two parts, the pressure change caused by the adjustment of other valves and the volume change of the insulation space caused by the sloshing of liquid tanks [11, 30]. The former kind of disturbance can be represented by the step signal, and the latter can be represented by the white noise. The disturbance \( d \) in Figure 7 is used to represent the above compound influences.

In order to verify the effectiveness and robustness of the multitechnique concise robust controller, a simulation with
disturbance is conducted. Through reasonable adjusting of the parameters in equation (8), one can set $T_0 = 0.2$, $\rho = -1$, $\epsilon = 0.001$, and $\omega = 1$. In this case, the step reference $r(s) = 1$ and a step disturbance $d(s) = -1$ are loaded along with the control input at $t = 30$ s, as well as the white noise disturbance that exists throughout the whole process. Figure 8 presents the result of the control efforts and system response. Furthermore, for the quantity purpose, the main performance indexes of the test are listed in Table 1. It is obvious that the proposed control scheme can guarantee the desired robustness specification of the closed-loop system, and all the performance indexes are satisfactory, especially the controller output is reasonable, and the overshoot is small enough.

To verify the effectiveness and merits of the proposed multitechnique concise robust control law further, one takes a comparison simulation test. For comparison, the compared control laws are designed with two other methods to tackle the time-delay problem, respectively. The first method is ignoring the time delay directly, and another one is using...
the first-order Padé approximation to replace the time delay. Following [26], the time-delay term in equation (3) can be replaced as

\[ G_2(s) = e^{-0.25s} \frac{1}{0.25s + 1}. \]  

(9)

Repeat the abovementioned controller design processes (5)–(7), the compared controller is obtained as follows:

\[ K_2(s) = \frac{0.25s + 1}{T_0s + 2} \left( \frac{0.78 \varepsilon + \rho + \frac{\varepsilon}{3.25T_0s} + \frac{s}{3.25T_0}}{3.25T_0s} \right). \]  

(10)

The control diagram of this method is shown in Figure 9. All the parameters are set the same as before.

The comparison result of the three methods to tackle time delay is illustrated in Figure 10. From that, all of the three control schemes are with the analogous robustness. However, applying the first-order Padé approximation will cause the controller to be sensitive to the disturbances which are not conducive to the protection of the control valve and consume more energy, and directly ignoring the time-delay term will not only introduce a larger overshoot but also enlarge the controller output. Therefore, the multitechnique concise robust control scheme with applying the SP has better control performance than the other two schemes.

Especially, another comparison simulation test is carried out to explain the advantages of employing a bipolar sigmoid function as the nonlinear-driven function for the control law. In short, the merit of using the bipolar sigmoid function as the nonlinear feedback is to suppress interference and output minor control action with the same control performance, which contributes to minimize valve wear and reduce waste of resources, e.g., energy and nitrogen. Figure 11 shows the responses of the controller and the system, with or without nonlinear feedback, under a large disturbance. In this comparison simulation test, the interference \( d \) in Figure 7 is replaced by a single triangular signal existing for 0.5 s with a peak value of 4, which is employed as a large disturbance, and other parameters are kept the same as aforementioned. It is obvious that the control law with nonlinear feedback acquires a smaller control output and a better anti-interference performance in the system response despite the time return to balance becomes a little longer.

5. Conclusions

This note discusses the pressure maintenance problem of the insulation space of membrane-type LNG carriers. And according to the characteristics of nonlinearity, instability, and time delay of this problem, a novel multitechnique concise robust control scheme based on the MMT, CGSA, SP, and NFT is proposed for solving this problem. A set of simulations are conducted to verify the effectiveness and robustness of the proposed control scheme. Above all, a simulation with the appropriate parameter setting and the further quantitative analysis are introduced to illustrate its control performance. In addition, a comparative simulation with other two time-delay processing methods, is performed to demonstrate its superiority. Finally, other simulations are carried out to explain the merits of using the bipolar sigmoid function as nonlinear feedback. All the results show that the multitechnique concise robust control scheme proposed in this note has not only stronger robustness and steady-state performance but also energy-saving performance.

However, this work naturally cannot attend to every detail of the control design, and the actual situation is far more complicated than the simulation condition (e.g., the control valves cannot response as fast as the simulation results). The further work will focus on building a more accurate system model, e.g., the model of the valve needs to be considered, and so on. The related results will be reported elsewhere.

Data Availability

All data generated or analyzed during this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was partially supported by the National Science Foundation of China (Grant no. 51679024), the Fundamental Research Funds for the Central University (Grant no. 3132016315), and the University 111 Project of China (Grant no. B08046).

References

[1] BP, “BP statistical review of world energy 2018: two steps forward, one step back,” 2018, https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-statistical-review-of-world-energy-2018.html.
[2] W. C. Sung, J. U. Roh, M. Sun Kim, and I. L. Woo, “Analysis of two main LNG CCS (cargo containment system) insulation boxes for leakage safety using experimentally defined thermal properties,” Applied Ocean Research, vol. 37, pp. 72–89, 2012.
[3] W. C. Niu, G. L. Li, Y. L. Ju, and Y. Z. Fu, “Design and analysis of the thermal insulation system for a new independent type B LNG carrier,” Ocean Engineering, vol. 142, pp. 51–61, 2017.
[4] M. S. Chun, M. H. Kim, W. S. Kim, S. H. Kim, and J. M. Lee, “Experimental investigation on the impact behavior of membrane-type LNG carrier insulation system,” Journal of Loss Prevention in the Process Industries, vol. 22, no. 6, pp. 901–907, 2009.
[5] J. O. Dong, J. M. Lee, M. S. Chun, and M. H. Kim, “Reliability evaluation of a LNGC insulation system with a metallic secondary barrier,” Composite Structures, vol. 171, pp. 43–52, 2017.
[6] H. Y. Young, B. G. Kim, and D. G. Lee, “Cryogenic reliability of composite insulation panels for liquefied natural gas (LNG) ships,” Composite Structures, vol. 94, no. 2, pp. 462–468, 2012.
[7] H. Y. Young, B. G. Kim, and D. G. Lee, “Cryogenic reliability of the sandwich insulation board for LNG ship,” Composite Structures, vol. 95, pp. 547–556, 2013.
[8] J. Choe, K. H. Kim, D. Lee, C. S. Bang, and D. G. Lee, “Glass composite vibration isolating structure for the LNG cargo
containment system,” Composite Structures, vol. 107, pp. 469–475, 2014.

[9] S. H. Yoon, K. H. Kim, and D. G. Lee, “Improvement of the adhesive peel strength of the secondary barrier with level difference for LNG containment system,” Composite Structures, vol. 95, pp. 528–538, 2013.

[10] Q. H. He, J. C. Yin, and W. J. Zhang, “Related operation essentials of membrane types LNG carriers on 308 considering the pressure of cargo tank and insulation space,” Ship & Ocean Engineering, vol. 44, no. 6, pp. 6–9, 2015.

[11] Y. Shin and Y. P. Lee, “Design of a boil-off natural gas reliquefaction control system for LNG carriers,” Applied Energy, vol. 86, no. 1, pp. 37–44, 2009.

[12] J. Romero Gómez, M. Romero Gómez, J. Lopez Bernal, and A. Baaliña Insua, “Analysis and efficiency enhancement of a boil-off gas reliquefaction system with cascade cycle on board LNG carriers,” Energy Conversion and Management, vol. 94, pp. 261–274, 2015.

[13] X. Zhang and X. Jia, “Solving robust controller of unstable process using mirror-injection method,” Systems Engineering and Electronics, vol. 22, no. 4, pp. 10–12, 2000.

[14] X. Zhang and G. Zhang, “Novel robust control design for unstable systems with dual pole and dual zero,” Control & Cybernetics, vol. 42, no. 3, pp. 613–625, 2013.

[15] G. Zhang, X. Zhang, and W. Guan, “Stability analysis and design of integrating unstable delay processes using the mirror-mapping technique,” Journal of Process Control, vol. 24, no. 7, pp. 1038–1045, 2014.

[16] G. Zhang, X. Zhang, and W. Zhang, “Robust controller synthesis for high order unstable processes with time delay using mirror mapping technique,” ISA Transactions, vol. 59, pp. 10–19, 2015.

[17] X. Zhang, Ship Motion Concise Robust Control, Science Press, Beijing, China, 2012.

[18] W. Guan, X. Zhang, and X. Wang, “Nonlinear robust control for ship steering system based on integral backstepping method,” Navigation of China, vol. 32, no. 3, pp. 66–70, 2009.

[19] X. Zhang and W. Guan, “Modified simple robust control of course keeping for large inertia ships,” Navigation of China, vol. 33, no. 3, pp. 1–5, 2010.

[20] X. Zhang and Y. Jin, “Robust PID controller based on closed-loop gain shaping algorithm and its application,” 2009 International Conference on Machine Learning and Cybernetics IEEE, pp. 1898–1903, Baoding, China, 2009.

[21] N. Abe and K. Yamanaka, “Smith predictor control and internal model control – a tutorial,” in Proceedings of the SICE 2003 Annual Conference, pp. 1383–1387, IEEE, Fukui, Japan, 2003.

[22] T. Liu, W. D. Zhang, Y. Z. Cai, and D. Y. Gu, “New modified Smith predictor scheme for integrating and unstable processes with time delay,” IEEE Proceedings-Control Theory and Applications, vol. 152, no. 2, pp. 238–246, 2005.

[23] D. Zhao, T. Zuo, and Z. Wang, “Progress in study of Smith predictor controller,” Chemical Industry And Engineering Progress, vol. 29, no. 8, pp. 1406–1410, 2010.

[24] M. R. Matasůek and A. I. Ribić, “Control of stable, integrating and unstable processes by the Modified Smith Predictor,” Journal of Process Control, vol. 22, no. 1, pp. 338–343, 2012.

[25] A. O’Dwyer, “A summary of PI and PID controller tuning rules for processes with time delay. Part 2: PID controller tuning rules,” IFAC Proceedings Volumes, vol. 33, no. 4, pp. 211–216, 2000.

[26] Q. Jin, L. Quan, X. Wang, and F. Qi, “Base on all-pole approximation a new internal model PID control method for the system with time delays,” in Proceedings of the International Conference on Mechatronics & Automation, pp. 268–273, IEEE, Changchun, China, 2009.

[27] X.-K. Zhang and G.-Q. Zhang, “Design of ship course-keeping autopilot using a sine function-based nonlinear feedback technique,” Journal of Navigation, vol. 69, no. 2, pp. 246–256, 2016.

[28] Q. Zhang, X.-K. Zhang, and N.-K. Im, “Ship nonlinear feedback course keeping algorithm based on MMG model driven by bipolar sigmoid function for berthing,” International Journal of Naval Architecture and Ocean Engineering, vol. 9, no. 5, pp. 525–536, 2017.

[29] Y. Fan, D. Mu, X. Zhang, G. Wang, and C. Guo, “Course keeping control based on integrated nonlinear feedback for a USV with pod-like propulsion,” Journal of Navigation, vol. 71, no. 4, pp. 878–898, 2018.

[30] J. R. Cho, S. W. Park, H. S. Kim, and S. Rashid, “Hydroelastic analysis of insulation containment of LNG carrier by global-local approach,” International Journal for Numerical Methods in Engineering, vol. 76, no. 5, pp. 749–774, 2008.