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Pressure Control of Insulation Space for Liquefied Natural Gas Carrier with Nonlinear Feedback Technique

Jinghua Cao [1,2,*], Xianku Zhang [1,*] and Xiang Zou [2]

[1] Key Laboratory of Marine Simulation & Control, Dalian Maritime University, Dalian 116026, China
[2] College of Computer and Software, Dalian Neusoft University of Information, Dalian 116023, China; zoux@neusoft.edu.cn
* Correspondence: caojh75@163.com (J.C.); zhangxk@dlmu.edu.cn (X.Z.); Tel.: +86-0411-8483-5100 (J.C.); +86-0411-8472-9572 (X.Z.)

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Abstract: This paper introduces a novel control strategy into the insulation space for liquid natural gas carriers. The control strategy proposed can improve the effects of control for differential pressure and reduce the energy consumption of nitrogen. The method combines a nonlinear feedback technique with a closed-loop gain shaping algorithm (CGSA). It is designed for the pressure control system which is vital for liquid natural gas carriers (LNGCs) in marine transportation. The control error is modulated using nonlinear function. The deviation signal is replaced with a nonlinear feedback signal. Comparison experiments are conducted under different conditions to prove the effectiveness of this strategy. This paper compares three control strategies: a control strategy with nonlinear feedback based on CGSA, a control strategy without nonlinear feedback based on CGSA, and a two-degree-of-freedom (DOF) control strategy. The simulation results show that this control strategy with nonlinear feedback performs better than the other two. The average reduction of control input is about 38.8%. The effect of pressure control is satisfactory.

Keywords: nonlinear feedback; CGSA; control; LNG carrier

1. Introduction

A liquefied natural gas carrier (LNGC) is a special ship used to transport liquid natural gas (LNG) cargo at low temperature (−163 °C) [1]. The common categories of LNGCs are membrane type or MOSS type. The containment systems of the membrane type are mainly the Gaz Transport (GT) NO. 96 system and Techngaz (TGZ) Mark III system [2]. The GT NO. 96 system is provided with an insulation layer. The insulation layer consists of two layers of insulation box. There is a partition inside the insulating box, and the box is filled with expanded perlite [3]. This kind of containment system needs to maintain a certain pressure and keep its internal inerting state. It also needs to prevent heat exchange between the tank and the outside [4,5]. The insulation layer can effectively isolate the liquid natural gas inside the tank from the external environment and prevent heat transfer between the interior of the tank and the external environment [6]. Another important role is to ensure that the tank shape is complete by maintaining the pressure difference between the primary and secondary insulating layers. Usually, the maintenance of the pressure difference is achieved by filling nitrogen or outdrawing nitrogen from the insulation space [7]. Thus, the insulation layer becomes the most important part of containment system. Pressure control technology of the insulation layer is one of the important technologies of membrane LNGCs. However, nitrogen is very expensive. How to control the pressure difference of the insulating space by adjusting the rate of nitrogen effectively and how to save the resource of nitrogen are important issues to be considered.

Simple proportion integral differential (PID) control technology is commonly used in engineering. This method is easily implemented and can achieve the expected control, but energy loss is rarely considered. Therefore, this paper proposes a solution to this problem.

Firstly, considering the balance between control effects and energy-saving effects, a better alternative control should be considered. The essence of nonlinear feedback control is an alternative choice for a PID controller.

Secondly, the nitrogen provided by the system on board is used to complete the inerting of the insulation space. The process requires a large amount of nitrogen. The flow rate of nitrogen and the pressure difference are a functional relationship. The pressure difference can be controlled by adjusting the rate of nitrogen. If the supply rate of nitrogen can be properly adjusted, more energy will be saved, which brings greater economic benefits.

The purpose of this paper is to optimize the control effects so that it can save energy and improve economic efficiency. At the same time, it can achieve the desired control effect.

The work of this paper is mainly divided into the following sections: research work on feedback control recently, nonlinear feedback principle, insulation layer description and pressure control, controller design, simulation results and analysis, and conclusion and discussion.

2. Literature Review

The system of pressure control for insulation spaces is an unstable, nonlinear, complex system with time-delay at the same time. Feedback control technique can provide a solution method. The feedback control is realized by feeding back the output to the controller and affecting the controlled variable. The controller determines to take actions and regulate the process variable by making use of the information of the current process variable [8]. This is the most common and simple structure to control the chemical process. Feedback control is used to maintain the output variable at a certain point set by the user. Usually the feedback signal is linear. However, the system is nonlinear, immeasurable, and uncertain, especially if there is coupling coexistence. The design of the control method for this kind of system is met with constant challenges. Thus, the tools used to design the control method in a nonlinear system include: linearization, integral control, gain scheduling, feedback linearization, synovial control, Lyapunov redesign, back stepping, slave control, and high gain observer [9]. Recently, the transient performance of nonlinear systems has achieved much attention. Many reports have appeared about this area of study. Na et al. proposed a nonlinear adaptive control method [10] to solve the problem of transient performance or steady-state tracking. Wang et al. [11] proposes a robust control method for an affine nonlinear system with full state feedback linearization. This method had a simple and direct effect. Guan et al. [12] designed a controller with dynamic output feedback on a cone complementary linearization procedure. This controller is used in a linear time-invariant system (LTI) with actuator saturation. Chen et al. [13] proposed a kind of nonlinear system with an actuator controlled by controller with composite nonlinear feedback (CNF) [13]. The controller of CNF was studied by Lu et al. [14] to solve the performance of the transient for the strict-feedback nonlinear system with input saturation. However, there is less discussion about the energy input of the control. A nonlinear feedback scheme with energy-saving was proposed by Zhang [15]. The energy conservation problem was discussed for the first time. The technique was applied to the control of a ship course-keeping autopilot and achieved good results [16–18]. Chen et al. [19] designed an adaptive neural fuzzy interference system (ANFIS) course-keeping controller with the technique in [15] to make the parameters easy to adjust. Zhang introduced nonlinear feedback with a nonlinear sine function modulated error signal into the longitudinal motion control for hydrofoils and the energy consumption. The system is an unstable multiple-input multiple-output (MIMO) system. Thus, nonlinear feedback is also applicable to MIMO systems [20]. Fan et al. [21] applied a nonlinear technique proposed in [15] into the motion control of an unmanned surface vehicle (USV) in heavy sea states. There is less discussion about the pressure control of insulation spaces for LNG carriers and the nitrogen saving problem with this technique. Based on previous research [15–21], this paper applied the nonlinear control technique to the pressure control of insulation space. The controller in this paper is designed with nonlinear feedback based on a closed-loop gain shaping algorithm (CGSA). In the comparison experiment, both the effect of control and the input of energy with this technique are better than with the comparison techniques. The results are satisfactory. The controller designed in this paper has the advantages of simple construction and easy implementation in industry.

3. Nonlinear Feedback

Nonlinear feedback is technology using the feedback signal to substitute the control error. This signal is the nonlinear function of the deviation between system output and input. The performance of the control system can be improved by modulating the control error function. At the same time, the construction of the control system is not changed. The nonlinear feedback control configuration is shown in Figure 1.

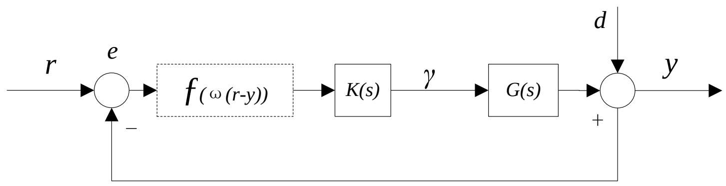

Figure 1. Nonlinear feedback control configuration.

It should be noted, the feedback control system is driven by $f(\omega(r-y))$ which is a nonlinear function, while ω is system frequency designed to adjust to save energy and e is substituted by $(r-y)$. The dotted line of the rectangle indicates that it is to handle the error e ($e = r - y$) not the multiplication with e. $K(s)$ is the controller to be designed and $G(s)$ is the control plant. It is important to find a stable K to achieve the better performance of control and to find a suitable driven function. The main work also includes testing performance of the controller in the form of $K \cdot f(\omega(r-y)$ with nonlinear feedback.

The technique is similar to those applied in neural network, fuzzy control, and optimizing genetic algorithms (GA). Certainly, the premise is to ensure the input of the nonlinear function to acquire a preferable effect. From Figure 1, the describing function of $f(\omega(r-y))$ can be written as $F(u)$. According to reference [16], the influence on the steady state for a closed loop system with input of step signal can be expressed in Equation (1).

$$e(\infty) = \underset{t\to\infty}{lim}(r-y) = \underset{s\to 0}{lims}\frac{1}{1+GKF}\frac{r}{s} \tag{1}$$

Effect on dynamic performance of the closed loop system can be obtained as Equation (2).

$$\frac{y}{r} = \frac{GKF}{1+GKF} \tag{2}$$

Effect on the output of controller can be obtained as Equation (3).

$$\frac{\gamma}{r} = \frac{KF}{1+GKF} \tag{3}$$

The demonstration process of mathematical derivation is presented in reference [16]. As there is no extra effect on the steady state and dynamic performance of the system, sine driven function is suitable for the nonlinear feedback system, and it can also save the energy of the system.

4. Problem Formulation and Controller Design

The pressure control of the insulation space is characterized by nonlinear, complex, unstable, significant time delay. Before establishing the mathematical model suitable, some hypothesis should be made first. Assumptions: (1) under certain circumstances, the sun exposure and atmospheric temperature are constant and do not change with time and place, and the seawater temperature is also a constant value; (2) for the cabin, the thickness of each part is uniform, ignoring the local change in thickness; (3) the heat from the outside is used for evaporation of the surface liquid cargo, and the gas and liquid surfaces in the tank are saturated. Figure 2 shows the diagram of a closed loop pressure control system.

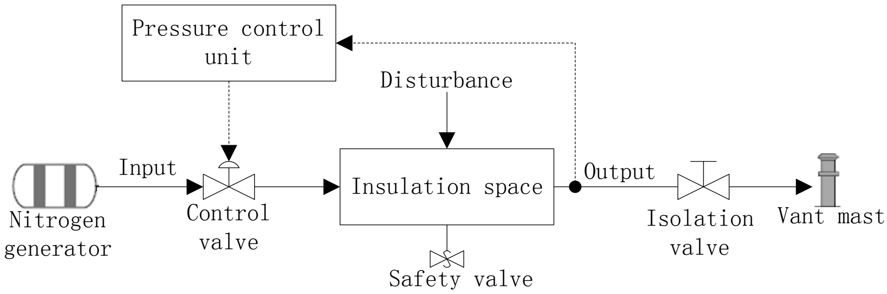

Figure 2. Loop pressure control system of insulation space.

It should be noticed that this research only considers the state of the system on the balance working point. That means the study only pays attention to the influence of the control unit on the speed when the safety valve is not working. The nitrogen is produced by the nitrogen generator. The flow rate is controlled by the pressure control unit. Nitrogen passes through the manifold into the primary and secondary insulation space to maintain the stable pressure in the space. Excess nitrogen will be released from the vant mast and the isolation valve is opened. There are safety valves on the primary and secondary insulating space manifolds in case of emergency. Each compartment is provided with safety valves. When the pressure exceeds the atmospheric pressure, the safety valve will be opened. In addition, external temperature, wind disturbance, wave disturbance, and the disturbances caused by cargo handling can cause changes to the pressure difference in the insulation space.

A controller should be designed and used to control the nitrogen supply rate. The percentage opening of control valve decides the input flow of N_2 which is related to the pressure difference in the insulating space. The pressure required is between 0.2 kPa ~0.4 kPa in the insulation space.

According to [22,23], the ratio of pressure difference and nitrogen supply rate can be linearized near the equilibrium point P_{e0}= 2.0 mbar, u_0= 42 m^3/h. Let $K_0 = 3.25,\ T_0 = 0.78,\ \tau = 0.25$. A system transfer function of linearization is given in Equation (4) below.

$$G(s) = \frac{\Delta P_e(s)}{\Delta u(s)} = \frac{K_0}{s(s - T_0)} e^{-\tau s} \tag{4}$$

If the time delay is not considered, $G_0(s)$ can be expressed as below.

$$G_0(s) = \frac{K_0}{s(s - T_0)} \tag{5}$$

There is the right half plane (RHP) pole at $s = T_0$ in Equation (5), hence the system is unstable. In Equation (6), $G(s)$ is obtained with the mirror mapping technique proposed in reference [24–27].

$$G_0(s) = \frac{-K_0/T_0}{s(-(1/T_0)s + 1)} \quad G(s) = \frac{-K_0/T_0}{-s((1/T_0)s + 1)} \tag{6}$$

The frequency spectrum curve of T is used to design the controller. The curve can be regarded as a frequency spectrum curve of a second order inertial system approximately when the closing slope of the curve is -40 (dB/dec). The largest singular value is 1. That means the damping ratio is 1. Thus, it ensures that there is no peak value in the frequency spectrum of T. According to the CGSA proposed in [28,29], then Equation (7) is obtained.

$$\frac{1}{(T_1 s+1)^2} = \frac{GK}{1+GK} \quad K = \frac{1}{GT_1 s(T_1 s+2)} \tag{7}$$

T_1 is the constant of time in a closed loop system. It is approximately equal to the reciprocal of bandwidth frequency (here T_1= 0.2). K is the controller to be designed. Substituting Equation (6) into Equation (7), Equation (8) is obtained.

$$K = \frac{-((1/T_0)s+1)}{-(K_0/T_0)T_1(T_1 s+2)} = \frac{(1/T_0)s+1}{(K_0/T_0)T_1(T_1 s+2)} \tag{8}$$

Equation (8) is a proportion integral (PD) controller and a first-order inertial filter essentially. In principle, it cannot eliminate the static error of system. Therefore, a very small number is added to the denominator of $G(s)$ in Equation (6). The generalized control plant is changed into Equation (9).

$$G(s) = \frac{K_0/T_0}{s(1/T_0 s+1)+\varepsilon} \tag{9}$$

Substituting Equation (9) into Equation (7), the function of controller output (u) and system error (e) can be expressed by Equation (10).

$$K = \frac{u}{e} = \frac{1}{T_1 s+2}\left(\frac{1/T_0}{(K_0/T_0)T_1}s + \frac{1}{(K_0/T_0)T_1} + \frac{\varepsilon}{(K_0/T_0)T_1 s}\right) \tag{10}$$

In order to further enhance the effect of energy saving, $f(\omega(r-y))$ can be added to Equation (10). Here $f(\omega(r-y))$ takes $\sin(\omega e)$. So, Equation (11) can be achieved using the nonlinear feedback technology with sine function in [15,16]. The value of error input can be controlled within $\pm$ 1 with sine function.

$$u = \frac{1}{T_1 s+2}\left(\frac{1/T_0}{(K_0/T_0)T_1}s + \frac{1}{(K_0/T_0)T_1} + \frac{\varepsilon}{(K_0/T_0)T_1 s}\right)\sin(\omega e) \tag{11}$$

where, $\varepsilon < 0.01$ is a very small constant to eliminate the static error of the system and $\omega < 1$ is the gain coefficient of the regulated nonlinear feedback that makes the system energy efficient. After adjustment, the best effect is $\omega = 0.9$.

If the time delay is considered, $e^{-\tau s}$ in Equation (4) can be expressed with the 1st order Padé approximation as follows.

$$e^{-\tau s} \approx \frac{1}{1+\tau s} \tag{12}$$

In order to reduce the impact of pure time delay, the denominator of Equation (12) is added to Equation (13). Then, u is the controller designed finally.

$$u = \frac{(\tau s+1)}{T_1 s+2}\left(\frac{1/T_0}{(K_0/T_0)T_1}s + \frac{1}{(K_0/T_0)T_1} + \frac{\varepsilon}{(K_0/T_0)T_1 s}\right)\sin(\omega e) \tag{13}$$

5. Simulation and Analysis

In order to prove the effectiveness of the controller designed in this paper, comparative simulation results are obtained. The compared control scheme comes from the literature [30]. The compared law is designed as a 2-DOF structure based on a modified Smith predictor. Two conditions are discussed: without disturbance and with disturbance.

5.1. Without Disturbance

Figures 3 and 4 show the comparison of system output and control input without interference. The real line represents control performance using nonlinear feedback. The dashed line describes the control without nonlinear feedback. The dotted line shows the performance of the controller designed with the scheme in reference [30].

There are three kinds of system response in Figure 3: without nonlinear feedback, the control law with 2-DOF, and with nonlinear feedback. The peak value of the step response is the shortest with nonlinear feedback. The value of M_{pt} (2.016) with the nonlinear feedback is closest to the set value 2. Overshoot is almost zero in nonlinear feedback.

Figure 4 shows the control input of three conditions: without nonlinear feedback, the control law with 2-DOF, and with nonlinear feedback. The energy consumption, namely the value of the mean absolute control effort (MAC) for nonlinear feedback is 50.97%. It is less than without nonlinear feedback and 33.8% less than 2-DOF. It is clear that control input is the smallest with the nonlinear feedback control proposed in this paper.

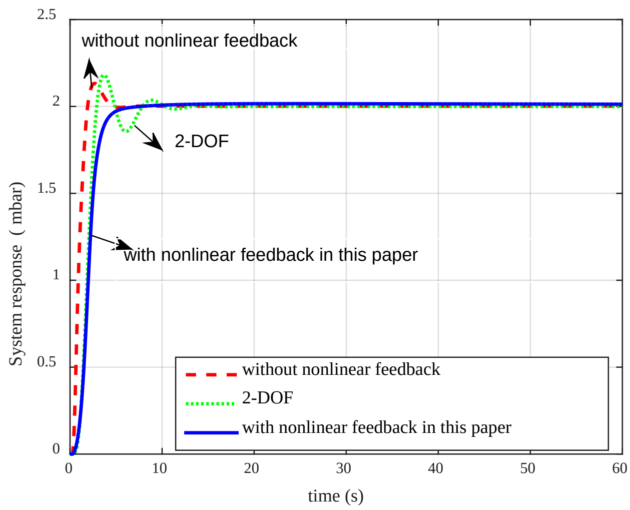

Figure 3. System response comparison without disturbance.

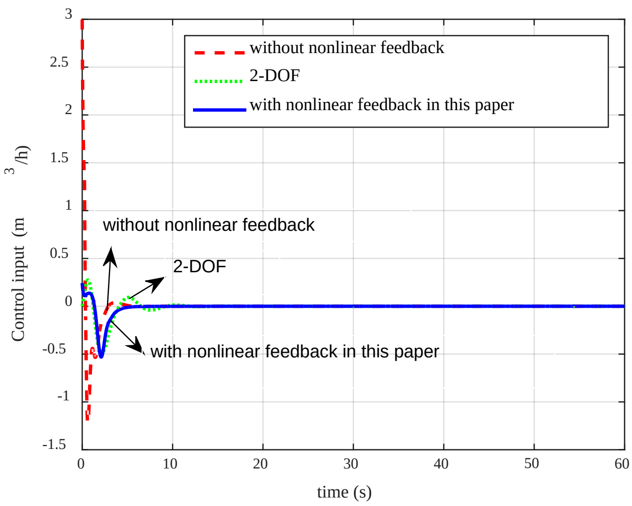

Figure 4. Control input comparison without disturbance.

It is clear that the effect of the control with the nonlinear feedback is better. The values of parameters are shown in Table 1.

Table 1. Parameters of performance calculation comparison.

Controller	M_{pt}	C_{ss}	*Overshoot* (σ_p%)	T_r	T_s	T_p
Without nonlinear feedback	2.133	2.002	6.54	1.913	7.292	2.634
2-DOF	2.181	2	9.05	2.911	19.824	3.743
With nonlinear feedback in this paper	2.016	2.016	0.0	7.514	7.514	18.159

Note: the rise time of response is defined as T_r. M_{pt} is the peak value of step response. C_{ss} is the value of stability state. The value of time to reach peak is defined as T_p. *Overshoot* is defined as the equation: $\sigma_p = \frac{M_{pt}-C_{ss}}{C_{ss}} \times 100\%$.

5.2. With Disturbance

In this section, there are three kinds of simulations performed. The parameters remain unchanged during the test.

In order to test the robustness of the scheme, disturbances are added at 30 s. The external disturbances mainly come from the shipping, cargo handling, the change of temperature outside, the interference of wind and wave currents, as well as the ship's violent shaking caused by bad sea conditions. Three disturbance signals are chosen: the step signal, the ramp signal, and white noise. The step signal disturbance rejection test is shown in Figures 5 and 6.

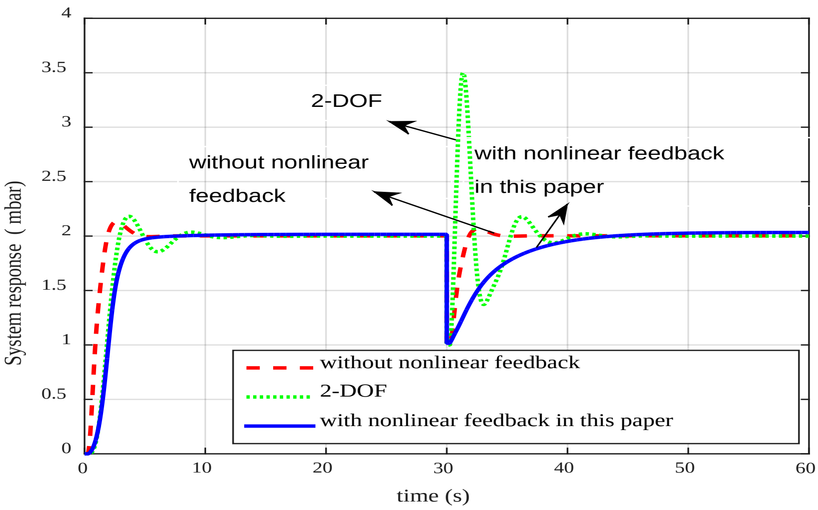

Figure 5. System response comparison with step signal.

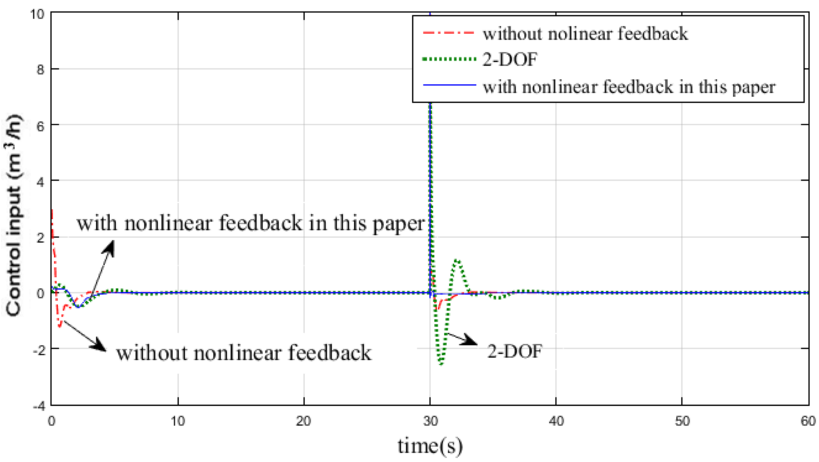

Figure 6. Control input comparison with step signal.

The ramp signal disturbance rejection test is shown in Figures 7 and 8.

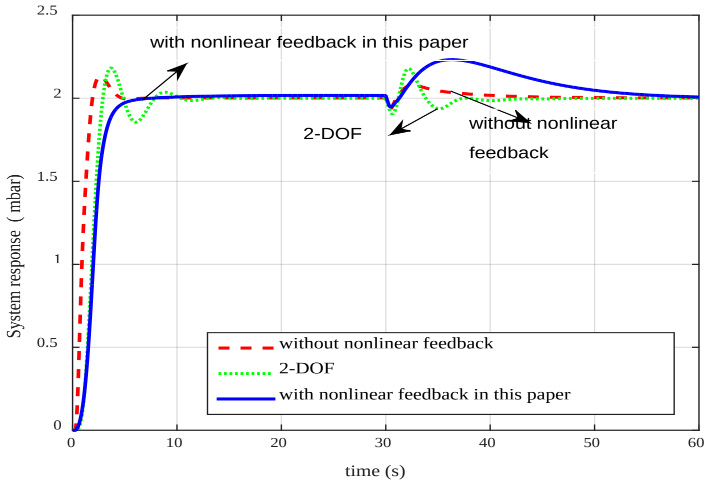

Figure 7. System response comparison with ramp signal.

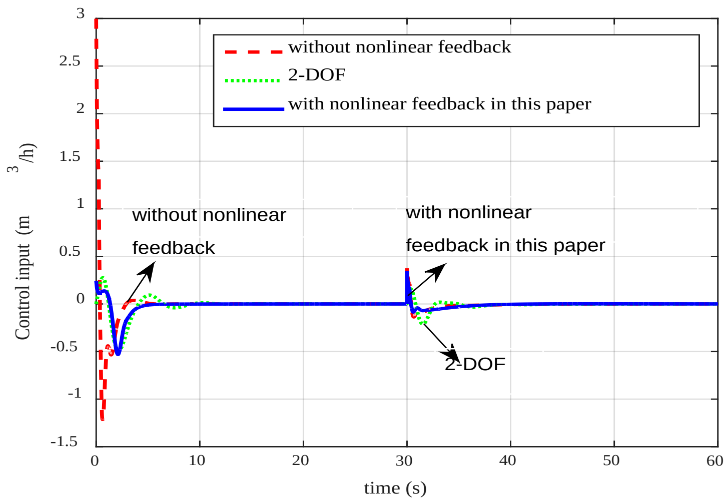

Figure 8. Control input comparison with ramp signal.

The white noise disturbance rejection test is shown in Figures 9 and 10.

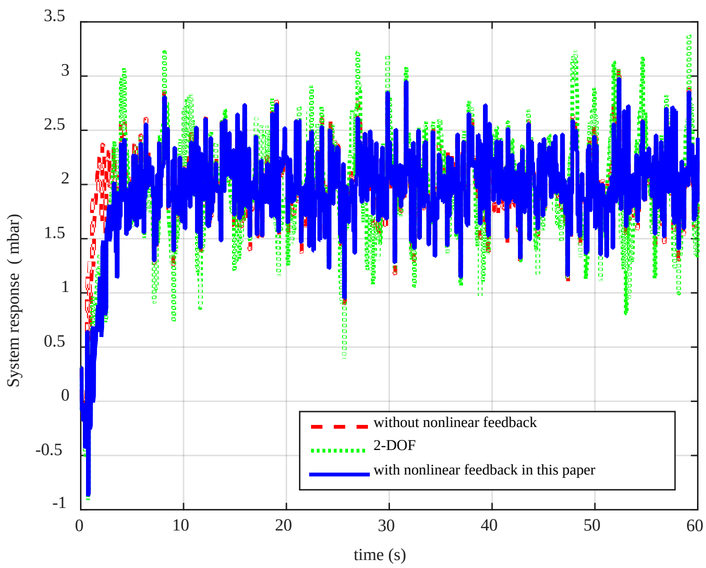

Figure 9. System response comparison with white noise disturbance.

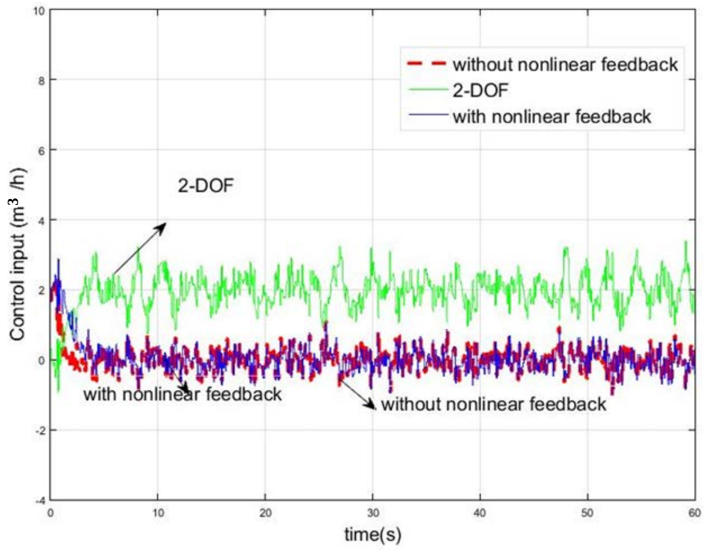

Figure 10. Control input comparison with white noise disturbance.

Furthermore, in order to provide quantification, the measure of these algorithms is based on the following popular performance metrics. It includes the mean absolute error (MAE), the mean absolute control effort (MAC), the mean squared error (MSE), and the total variation (TV) of control. The system response can be evaluated by the value of MAE and MSE. The energy consumption and smoothness is evaluated by the value of MAC and TV. The formula group (Equation (14)) is used to calculate the value of each evaluation metric. The results of quantitative comparison show the nonlinear feedback algorithm of this paper is effective.

$$\begin{cases} \mathrm{MAE} = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|e(t)|\mathrm{d}t = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|r(t)-y(t)|\mathrm{d}t \\ \mathrm{MSE} = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|e(t)|^2\mathrm{d}t = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|r(t)-y(t)|^2\mathrm{d}t \\ \mathrm{MAC} = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|u(t)|\mathrm{d}t \\ \mathrm{TV} = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty}|u(t+1)-u(t)|\mathrm{d}t \end{cases} \tag{14}$$

The values of performance for different controllers are listed in the Table 2.

Table 2. Performance comparison of different controllers.

Plant	Controller	MAE	MAC	TV	MSE
Normal	Without Nonlinear Feedback	0.03723	0.02739	0.08735	0.04945
	2DOF	0.127	0.02029	0.03404	0.2127
	Nonlinear Feedback	0.08239	0.01343	0.0267	0.1076
Disturbed	Without Nonlinear Feedback	0.045	0.03393	0.09265	0.04982
	2DOF	0.1738	0.02798	0.0441	0.2406
	Nonlinear Feedback	0.1241	0.01986	0.03128	0.1153

From the results of the simulations above, it is obvious that the nonlinear feedback scheme has better control performance than the scheme without nonlinear feedback in this paper. In addition, the control input of nonlinear feedback is obviously lower than others without nonlinear feedback. That means the controller with nonlinear feedback in this paper has better energy-saving and strong anti-interference ability. The result shows that the control method proposed is satisfactory, robust and cost-effective. The controller designed in this paper adopts lower order, so it is easy to be implemented in industrial process.

6. Conclusions

This paper discusses pressure control and energy saving for the insulation space of LNG carriers. A novel optimized controller is designed with a nonlinear feedback technique based on a CGSA. Comparative simulations are conducted by comparing with the 2-DOF structure based on a modified Smith predictor and the scheme without nonlinear feedback based on the same algorithm in this paper. The results show that the control scheme with the nonlinear feedback technique proposed in this paper not only has stronger robustness but also steady-state performance. At the same time, the scheme in this paper saves nitrogen flow and reduces energy loss, and it would also be helpful to shipbuilding and optimizing the process of handling. The control strategy in this paper can be used for other system models and provides a good reference for LNG control system design.

The research in this paper is limited to the established assumptions, and the actual situation is more complicated. For example, typical control valves do not move as fast as the results. When those control logics are reflected on a typical slow valve, the model of the valve must be considered. When the pressure difference achieves a certain value, the valve will work. Thus, a first-order inertial system with pure time delay can be added to the ideal proportional mathematical model. The nonlinear feedback technique in this paper only improves the system output performance and saves energy when the feedback error is small. It is necessary to conduct in-depth theoretical analysis in future research work for the case of larger feedback errors.

Author Contributions: J.C. has been the main author of the manuscript and did all the study design, data analysis, figures and writing. X.Z. (Xianku Zhang) designed the paper together with J.C. and performed the parameter adjustment. X.Z. (Xiang Zou) contributed to the literature search, data collection, data interpretation and was involved in interpreting the simulation results. All authors reviewed and commented on the manuscript.

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