Research Article

A Nonlinear Power Feedback Improvement of the Ship Course-Keeping Controller

Yancai Hu(1), Wenxue Su(2), Qiang Zhang(1), Yan Zhang(1), and Caifan Wang(1)

1School of Navigation and Shipping, Shandong Jiaotong University, Weihai 264200, Shandong, China
2Qingdao Harbour Vocational & Technical College, Qingdao 266404, Shandong, China

Correspondence should be addressed to Qiang Zhang; zq20060054@163.com

Received 7 January 2022; Accepted 9 June 2022; Published 18 July 2022

Academic Editor: Xingling Shao

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In order to simplify the design process of the controller, improve the robustness of the system, and save the energy output of the controller, a controller improved by nonlinear feedback is designed. First of all, by constructing the Lyapunov function, the controller design process is simplified, and the nonlinear control law is avoided to cancel the nonlinear term of the system; then, the heading error processed by the power function is used to replace the nonlinear feedback term of the heading error itself; finally, the training ship “Yupeng” was used as an example for system simulation. Compared with the pure backstepping method, the simulation results show that the average energy cost of heading keeping of the proposed algorithm is reduced by 21.7%, and the maximum energy cost of heading tracking is reduced by 34.9%, with the strong anti-interference ability. Studies have shown that the introduction of nonlinear feedback terms can optimize the control system, save energy, and enhance robustness, which is of great significance in practical engineering applications.

1. Introduction

In order to reach the destination port as soon as possible and reduce fuel consumption during the voyage, the most ideal way for ships sailing at sea is to sail along the planned route. At the same time, it can reduce carbon dioxide emissions during the course of the ship’s course, save the fuel consumption of the ship in actual navigation, and respond to the national “carbon peak” call. However, due to the influence of wind, waves, currents, etc., it is difficult for general ships to sail along the planned route. Therefore, it is necessary to design a robust controller to overcome external disturbances to ensure that the ship sails along the set route. In response to this problem, many scholars have proposed many advanced control algorithms, such as PID [1, 2], sliding mode [3, 4], backstepping, radial basis function (RBF) neural network [5–9], fuzzy [10–12], and other control algorithms [13, 14]. In [13], an elliptical target encircling control policy of quadrotors subject to uncertainties and aperiodic signals updating based on pure bearing measurements was proposed and its effectiveness was verified by simulation. In [14], a quantized control capable of appointed-time performances for quadrotor attitude tracking was investigated, and in the controller-to-actuator channel, a hysteresis quantizer was developed which can transform the continuous control behavior into a stable discrete scalar to reduce the transmission burden and the amount of sampled data. Among them, the backstepping algorithm is a typical method to solve nonlinear control problems, and it is also a research hotspot in the field of nonlinear control of ship motion [15–17]; there have been many research results using hybrid methods to increase its adaptability or robustness in this research. For example, in [18], a control strategy that combines a backstepping recursive algorithm with a robust control algorithm is proposed, which improves the robustness of the algorithm; in [19], adaptive and nonlinear feedback techniques are added to the process of backstepping recursion, which improves the adaptability and robustness of the algorithm; in [20], robust integral backstepping, coordination, and terminal coordination control methods were proposed to achieve good course performance and reduce energy consumption in ship course control.
The problem of parameter uncertainty is generally divided into two or more steps when using the backstepping algorithm to design a nonlinear controller. If the controlled object is complex and the final nonlinear control methods have many undefined parameters, the design process is complicated. The nonlinear control strategy designed by the conventional backstepping recursive method generally cancels the nonlinear term of the system [21, 22]. In [23], the nonlinear ship heading control system with uncertain parameters and unknown control coefficients, the dynamic surface control (DSC) and Nussbaum gain function are combined with the backstepping algorithm, which has achieved good results. In [24], a direct model was proposed, which overcomes the shortcomings of the traditional adaptive strategy that the quality of the system transition process is degraded after the introduction of standardized signals by the traditional adaptive strategy by referring to the backstepping recursive adaptive control system strategy. In [25], researcher made contributions to the problem of designing ship course-keeping control strategy using backstepping algorithms.

In order to improve the control effect and reduce the energy consumption of the system, researchers have done a lot of work and found that [26–28] nonlinear feedback technology can achieve the same or even better control effect with less control energy [29]. Based on the above research results, the sine function [30, 31], bipolar sigmoid function [32], and arctangent function [33] driven by the nonlinear feedback algorithm have employed normally, but the power function is rarely used for nonlinear feedback algorithm combined with backstepping. This manuscript is dedicated to developing a simplified backstepping control system with improved nonlinear feedback power function to simplify the design process of backstepping control methods, reduce the number of undetermined parameters, improve robustness, and save the energy output of the controller. Because the designed control method has obvious energy-saving effects, the control strategy will be applied to engineering practice in the future to effectively reduce the fuel consumption and carbon dioxide emissions of vessels.

### 2. Establishment and Verification of Ship Model

This note takes the training ship “Yupeng” of Dalian Maritime University as an example, refers to [34, 35], and establishes the “Yupeng” Nomoto model, which is shown in Figure 1. In the figure, $\delta$ is the rudder angle; $\delta_e$ is the rudder angle error; $\dot{\delta}$ is the rudder turning rate; $\delta_{\text{max}}$ is the maximum rudder turning rate; $\delta_D$ is the interference; $\psi$ is the heading; $\psi$ is the turning rate; $s$ is the Laplace operator; $K$ is the turning ability index; and $T$ is the following index.

The nonlinear second-order Nomoto ship motion model is shown in [36]

$$\ddot{\psi} + \frac{T}{K} H(\psi) = \frac{K}{T} \delta,$$  \hspace{1cm} (1)

where $H(\psi) = a \dot{\psi} + b \psi^3$; among them, $a$ and $b$ are the parameters obtained by the least square (LS) method system identification [34].

This manuscript uses the ballast state data of the training ship “Yupeng” of Dalian Maritime University shown in Table 1 and takes the Simulink toolbox of MATLAB software to conduct ballast dextrorotation simulation experiments on the established “Yupeng” nonlinear Nomoto ship motion response model and compare it with the actual ship ballast dextrorotation test (see Figure 2). The result is shown in Figure 3.

The comparison results of the cyclic test simulation and the real ship are given in Table 2. The transverse diameter obtained by the simulation is 3.051 L, and the transverse diameter obtained by the actual ship test is 3.75 L; the advance diameters of the simulation and actual ships are basically the same. The comparison shows that the transverse agreement of the simulation results is 81.3%, and the overall agreement is 90.7%. The experimental results verify the effectiveness of the model [33].

### 3. Improved Backstepping Controller Design

The nonlinear control strategy of the ship is designed so that the actual heading direction follows the desired course. Let $x_1 = \psi, x_1 = \dot{x}_2 = \dot{\psi} = r$, then

$$\dot{x}_1 = x_2,$$  \hspace{1cm} (2)

$$\dot{x}_2 = f(x_2) + bu,$$ $y = x_1,$

$$f(x_2) = \frac{K}{T} H(\psi),$$

$$H(\psi) = a\dot{\psi} + b\psi^3,$$

$$b = \frac{K}{T}.$$
where \( y \subset \mathbb{R} \) is system input, \( u \) is the control strategy to be designed, and \( u = \delta \); let

\[
\begin{align*}
    z_1 &= x_1 - \psi_R, \\
    z_2 &= x_2.
\end{align*}
\]

(4)

If the final controller stabilization state variables are \( z_1 \) and \( z_2 \), the original system reaches uniform asymptotic stability at the equilibrium point \( x_1 = \psi_R, x_2 = 0 \).

A Lyapunov function was constructed:

\[
    V_1 = \frac{1}{2} z_2^2. \tag{5}
\]

Due to the differential relationship between \( z_1 \) and \( z_2 \), if \( z_1 \) is stabilized to the equilibrium point 0, then \( z_2 \) is also stabilized at the same time [24]; this is because if \( z_1 \) is stabilized to the equilibrium point 0, that is \( x_2 = x_1 = 0 \), then \( x_1 \) is a fixed value and \( \psi_R \) is also a fixed value, so it can be seen that \( z_1 \) is stabilized at the same time.

When constructing the Lyapunov function in this manuscript, the differential relationship between \( z_2 \) and \( z_1 \) is considered. If \( z_2 \) is stabilized to the equilibrium point 0, then \( z_1 \) is stabilized at the same time. This differential relationship between \( z_2 \) and \( z_1 \) has a certain generality in the actual system. For simplification, \( V_1 \) is constructed without the information of \( z_1 \), but it must be ensured that the control method is appropriately selected so that \( V_1 \) contains \( z_1 \) and finally, \( z_1 \) and \( z_2 \) are stabilized at the same time.

\[
    \dot{V}_1 = z_2 \cdot \dot{z}_2, \tag{6}
\]

\[
    \dot{z}_2 = \dot{x}_2 = f(x_2) + bu. \tag{7}
\]

To make \( V_1 \leq 0 \), the controller is designed:

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**Table 1: Parameters of ship Yupeng.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ballast condition</th>
<th>Full-load condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars ( L (m) )</td>
<td>189</td>
<td>189</td>
</tr>
<tr>
<td>Breadth (molded) ( B (m) )</td>
<td>27.8</td>
<td>27.8</td>
</tr>
<tr>
<td>Designed draught ( D (m) )</td>
<td>6.3</td>
<td>11.0</td>
</tr>
<tr>
<td>Block coefficient ( C_b )</td>
<td>0.661</td>
<td>0.72</td>
</tr>
<tr>
<td>Longitudinal center of gravity ( x_c (m) )</td>
<td>-4.04</td>
<td>-1.8</td>
</tr>
<tr>
<td>Volume of displacement ( V (m^3) )</td>
<td>220367.7</td>
<td>292689.3</td>
</tr>
<tr>
<td>Trial speed ( V (kn) )</td>
<td>17.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Rudder area ( A_r (m^2) )</td>
<td>31.67</td>
<td>38</td>
</tr>
<tr>
<td>Turning ability index ( K/s^{-1} )</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>Following index ( T/s^{-1} )</td>
<td>107.78</td>
<td>39.54</td>
</tr>
<tr>
<td>Maximum rudder angle ( \delta_{\max} )</td>
<td>35 ( ^\circ )</td>
<td>35 ( ^\circ )</td>
</tr>
<tr>
<td>Average rudder angle ( \delta_{\max} )</td>
<td>( \pm 5 ) ( ^\circ \cdot s^{-1} )</td>
<td>( \pm 5 ) ( ^\circ \cdot s^{-1} )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>13.14</td>
<td>18.80</td>
</tr>
<tr>
<td>( \beta )</td>
<td>16212.5</td>
<td>21459.9</td>
</tr>
</tbody>
</table>

---

**Table 2: Comparison results of real ship test and simulation.**

<table>
<thead>
<tr>
<th></th>
<th>Lateral tactical diameter</th>
<th>Longitudinal tactical diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real ship test</td>
<td>3.75 L</td>
<td>3.1 L</td>
</tr>
<tr>
<td>Simulation</td>
<td>3.05 L</td>
<td>2.9 L</td>
</tr>
<tr>
<td>( C_M )</td>
<td>81.3%</td>
<td>93.5%</td>
</tr>
<tr>
<td>( C_M' )</td>
<td></td>
<td>87.5%</td>
</tr>
</tbody>
</table>

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---
where \( k_1 > 0, \lambda > 0; \) both are controller design parameters. 

\[(1 + z_1)^w - 1 = \omega z_1 + \frac{1}{2} \omega^2 z_1^2 \omega (\omega - 1) + \frac{1}{6} \omega^3 z_1^3 \omega (\omega - 1) (\omega - 2).\]  

(9)

Equation (9) is substituted into (8), and from equation (2) to equation (7), (11) can be obtained:

\[
\begin{align*}
\dot{V}_1 &= z_2 \left[ f(x_2) + bu \right] = tz_2 \left[ f(x_2) + b - \frac{1}{b} \left[ f(x_2) - k_1 \left[ (1 + z_1)^w - 1 \right] \right] \right], \\
&= z_2 \left[ f(x_2) + \left[ f(x_2) - k_1 \left[ \omega z_1 + \frac{1}{2} \omega^2 z_1^2 \omega (\omega - 1) + \frac{1}{6} \omega^3 z_1^3 \omega (\omega - 1) (\omega - 2) \right] \right] \right], \\
&= 2x_2 f(x_2) - k_1 z_1 z_2 \omega - \frac{k_1}{2} \omega^2 z_1^2 \omega (\omega - 1) - \frac{k_1}{6} \omega^3 z_1^3 \omega (\omega - 1) (\omega - 2).
\end{align*}
\]

According to Young’s inequality [36], the following inequality holds:

\[-z_1^2 z_2 \leq \frac{1}{2} z_1^4 + \frac{1}{2} \omega^2 z_1^2.\]  

(11)

Equation (11) is substituted into (10), and (12) is obtained:

\[
\begin{align*}
\dot{V}_1 &\leq 2x_2 f(x_2) - k_1 z_1 z_2 \omega + \frac{k_1}{2} \left( \frac{1}{2} \omega^2 z_1^2 + \frac{1}{2} \omega^2 z_1^2 \right) \omega (\omega - 1) \\
&= -2b (\alpha z_2^4 + \beta x_2^4) - k_1 \frac{x_1}{h} \omega + \frac{k_1}{2} \omega (\omega - 1) \left[ \frac{1}{2} \left( \frac{x_1}{h} + \frac{\psi r}{h} \right) \right] \omega (\omega - 1) \\
&= -b (\alpha x_2^4 + \beta x_2^4) - k_1 \omega \omega (\omega - 1) (\omega - 2) \\
&= -2b (\alpha x_2^4 + \beta x_2^4) - k_1 \omega \omega (\omega - 1) (\omega - 2) \\
&= \left( 2b \alpha + k_1 \omega \omega - \frac{1}{4} k_1 \omega \omega (\omega - 1) \right) x_2^4, \\
&= \left( 2b \beta - \frac{k_1}{4} h \omega \omega (\omega - 1) + \frac{k_1}{6} h^2 \omega (\omega - 1) (\omega - 2) \right) x_2^4.
\end{align*}
\]

(12)

where \( h \) is the system sampling period. In formula 12, \( x_2 \) used to approximate \((x_1 - \psi r)/h)\) does not strictly follow the definition of mathematical derivative, but it is acceptable in control engineering.

Because \( b, \alpha, \) and \( \beta \) are all greater than 0, so as long as (13) and (14) holds

\[
2b \alpha + k_1 h \omega - \frac{1}{4} k_1 \omega \omega (\omega - 1) > 0.
\]

(13)

\[
2b \beta - \frac{k_1}{4} h \omega (\omega - 1) + \frac{k_1}{6} h^2 \omega (\omega - 1) (\omega - 2) > 0.
\]

(14)

So, \( \dot{V}_1 < 0 \) permanent establishment.

The inequalities (13)–(14) are solved, and the formula 16 is obtained.

\[
\frac{3}{2} h + 1 < \omega < 4 h.
\]

(15)

The sampling period of the general simulation experiment satisfies \( h \leq 1s \), and the sampling time selected in this manuscript is \( h = 0.5s \), which meets the requirements. At this time, the system design parameter \( \lambda \) must be able to guarantee the constant validity of \( \dot{V}_1 < 0 \) within the interval \((1.75, 2)\). It can be known from the Lyapunov stability theorem that the control strategy equation (8) designed in this manuscript can stabilize the entire system so that the system achieves uniform asymptotic stability at equilibrium point \( x_1 = \psi_r, x_3 = 0 \). The nonlinear control strategy solution process of equation (8) only constructs a Lyapunov function, and there are only two undetermined parameters \( k_i \) and \( \lambda \) in the control method. The controller design process and parameter selection are relatively simple.

4. Simulation

The “Yupeng” of Dalian Maritime University carried out a simulation experiment [37, 38]. To make the control plant simulation closer to marine practice, a set of rudder servo system is considered, angle limiter and revolution rate limiter. The manuscript considers that the ship’s course is affected by wind and waves during actual navigation and adds 6 levels of wind and wave interference in the simulation, and the simulation results with sea wave interference are obtained. Due to the complicated wind conditions during navigation, this article describes the wind interference equivalently as a combination of white noise and the equivalent rudder angle representing the corresponding wind level, so as to accurately describe the impact of wind on
ship navigation [39]. According to [34, 35], the “Yupeng” ship is in the 6th class wind and the wind side angle is 30°, and the wind equivalent rudder angle $\delta_{\text{wind}} = 0.8^\circ$ is calculated. The second-order oscillation link driven by white noise caused by the ocean wave interference caused by the 6-level wind is described by $[0.4198s/(s^2 + 0.3638s + 0.3675)]$. Simulink toolbox is used to illustrate the effectiveness of designed controller in MATLAB environment.

The desired heading is 60°, and the control effect is optimal when the controller parameter $k_1 = 0.0038$. The comparison results of backstepping control and nonlinear feedback control are shown in Figures 4 and 5. The red lines in Figures 4 and 5, respectively, represent the ship course-keeping effect and rudder angle effect under the control of the backstepping controller. It can be seen that when the ship turns to 60°, the adjustment time is about 250 s, the maximum steering amplitude is 35°, and the overshoot is 8°.

The energy consumption of the rudder is reflected in the stability of the steering, the number of rudder movements (above 0.5°), the action time, and the rotation range of the rudder blades [40]. Average rudder angle $\bar{\delta} = (1/(t_{n_i} - t_0)) \int_0^{t_{n_i}} |\delta(t)| dt$ ($t_0 = 0$, $t_{n_i}$ is the adjustment time) is used in this manuscript to consider system energy consumption. The average rudder angle is discretized as $J = (1/(t_{n_i} - t_0)) \sum_k |\delta(k)|$ [32], and the average rudder angle $\bar{\delta}_1 = 9.41^\circ$ is obtained.

In order to optimize the control and solve the problem of high energy consumption in the system, this manuscript is inspired by the literature [30–33], keeping the controller unchanged, and introducing nonlinear power function feedback into the system; that is, the processed heading error processed by the nonlinear power function replaces the original heading error as the input signal of the controller. The system design is shown in Figure 6 (in the figure, $\ln(\lambda u + 1)$ is the feedback term of the power function, and $d$ is the interference). During simulation, parameter $\lambda$ of the power function needs to be adjusted to the optimal control effect.

The effect of simulation control is optimal when parameter $\lambda = 0.6$ is selected. The blue lines in Figures 4 and 5, respectively, represent the ship course-keeping effect and rudder angle effect under the control of the power feedback controller. It can be seen that when the ship turns to 60°, the adjustment time is about 200 s, the maximum steering amplitude is 35°, the overshoot is 5°, and the average rudder angle $\bar{\delta}_2 = 7.52^\circ$ is calculated. In order to quantify the difference in energy consumption between the two, the concept of energy-saving ratio $P$ is introduced in this manuscript [28].

$$P = \frac{\bar{\delta}_1 - \bar{\delta}_2}{\bar{\delta}_1} \times 100\%.$$  \hspace{1cm} (16)

From the comparison of the two simulation results, it can be seen that after the nonlinear feedback of the power function is introduced, the energy cost performance of the controller is reduced by 20.2%.

In order to verify the control effect and energy-saving of the nonlinear feedback controller, the article conducted simulation experiments on heading keeping at 20°, 40°, 60°, and 80°, and the data obtained are shown in Table 3.

It can be seen from the data in Table 2 that after the introduction of power function nonlinear feedback control, the adjustment time is shortened and the average rudder angle is smaller in the entire control process. The above shows that the improved controller has more excellent control effect and the system is more energy-saving.

In the actual sailing process of ships, there are frequent turns. In order to study the control effect and energy-saving situation of the improved controller, the simulation experiment of ship course-tracking is carried out in this manuscript. The simulation environment of course-tracking remains the same as the course-keeping. The input heading
in this article is (± 20)°, and the frequency is 0.01 rad/s. The comparison results of backstepping control and nonlinear feedback control are shown in Figures 7 and 8. The red lines in Figures 7 and 8, respectively, represent the ship course-tracking effect and rudder angle effect under the control of the backstepping controller. The blue lines in Figures 7 and 8, respectively, represent the ship course-tracking effect and rudder angle effect under the control of the power feedback controller. It can be seen from Figure 7 that after the introduction of power function nonlinear feedback, the overshoot of the system is reduced, and the stabilization time is shortened, which shows that the improved controller has a more excellent control effect. It can be calculated from Figure 8 that the average rudder angle δ̅ = 5.96° of the entire control system before the introduction of power function nonlinear feedback, the average rudder angle δ̅ = 3.88° after the introduction of power function nonlinear feedback, and the energy-saving ratio is as high as 34.9%. The above further proves that the improved controller with power function nonlinear feedback has better control effect, and the system is more energy-saving.

In order to further verify the robustness of the improved nonlinear feedback controller, this manuscript uses Yupeng’s full-load data for simulation. The ship data and the parameters of the nonlinear Nomoto model of the “Yupeng”

<table>
<thead>
<tr>
<th>Steady course ψ(°)</th>
<th>Control type</th>
<th>Adjustment time t_n/s</th>
<th>Maximum rudder angle δ_max(°)</th>
<th>Average rudder angle δ(°)</th>
<th>Energy-saving ratio P/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Backstepping</td>
<td>250</td>
<td>31</td>
<td>6.85</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>Nonlinear feedback</td>
<td>200</td>
<td>17</td>
<td>5.04</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Backstepping control</td>
<td>300</td>
<td>35</td>
<td>7.94</td>
<td>25.1</td>
</tr>
<tr>
<td></td>
<td>Nonlinear feedback</td>
<td>250</td>
<td>32</td>
<td>5.95</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Backstepping</td>
<td>300</td>
<td>35</td>
<td>9.41</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>Nonlinear feedback</td>
<td>250</td>
<td>35</td>
<td>7.51</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Backstepping</td>
<td>280</td>
<td>35</td>
<td>11.66</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Nonlinear feedback</td>
<td>230</td>
<td>35</td>
<td>9.90</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Diagram of the nonlinear feedback system.

Figure 7: The rudder effect during the course-tracking.

Figure 8: The course-keeping effect of ship during the course-tracking.

Table 3: Temperature and wildlife count in the three areas covered by the study.
ship at full load can be obtained by calculation \[32, 33\]. The parameters are shown in Table 1. The data shown in Table 1 were used to conduct a simulation experiment of the ship turning to 60°, and the results are shown in Figures 9 and 10. The red line in Figures 9 and 10 is the control effect of the backstepping controller: the maximum rudder angle is 35°, the adjustment time is about 170 s, and the overshoot is 6°; the blue line is the control effect of the improved controller: the maximum rudder angle is 35°, the adjustment time is about 130 s, and the overshoot is 3°. It can be seen from the above that when the loading status of the ship changes, the improved controller designed in this manuscript still has a good control effect, and the system is robust.

5. Conclusions

In order to reduce the carbon emissions of ships during navigation, it is necessary to design more energy-saving and robust controllers. In this manuscript, the power function nonlinear feedback algorithm is introduced into the backstepping algorithm, and a nonlinear feedback course-keeping strategy is designed. The manuscript takes "Yupeng" as an example for simulation research, and the results show that the controller with nonlinear power feedback still has a good control effect under the wind and wave model. In the whole simulation process, the controller can respond well to the steering command, and the average rudder angle of the steering is small, which well protects the steering gear and saves energy. Research shows that the control strategy designed in this manuscript has excellent robustness and energy-saving advantages in actual ship navigation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author(s) declare(s) that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (grant number 51911540478); Key Research and Development Plan of Shandong Province (grant number 2019JZZY020712); Shandong Jiaotong University PhD Startup Foundation of Scientific Research and Shandong Jiaotong University Climbing Research Innovation Team Program (grant number SDJUC1802); and Research Project on Postgraduate Education and Teaching Reform in Shandong Province (SDYJG19217).

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