全浸没式水翼船起飞控制研究

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目录

1.1 研究目的与意义

研究目的：将重物移动系统与水翼系统相结合增强水翼船起飞过程的横摇控制能力

研究意义：提高电动水翼工作船在恶劣海况下的运营安全性

电动水翼工作船EF-12

Moth飞蛾级帆船

1.2 研究现状综述

全浸没式水翼船控制研究现状：

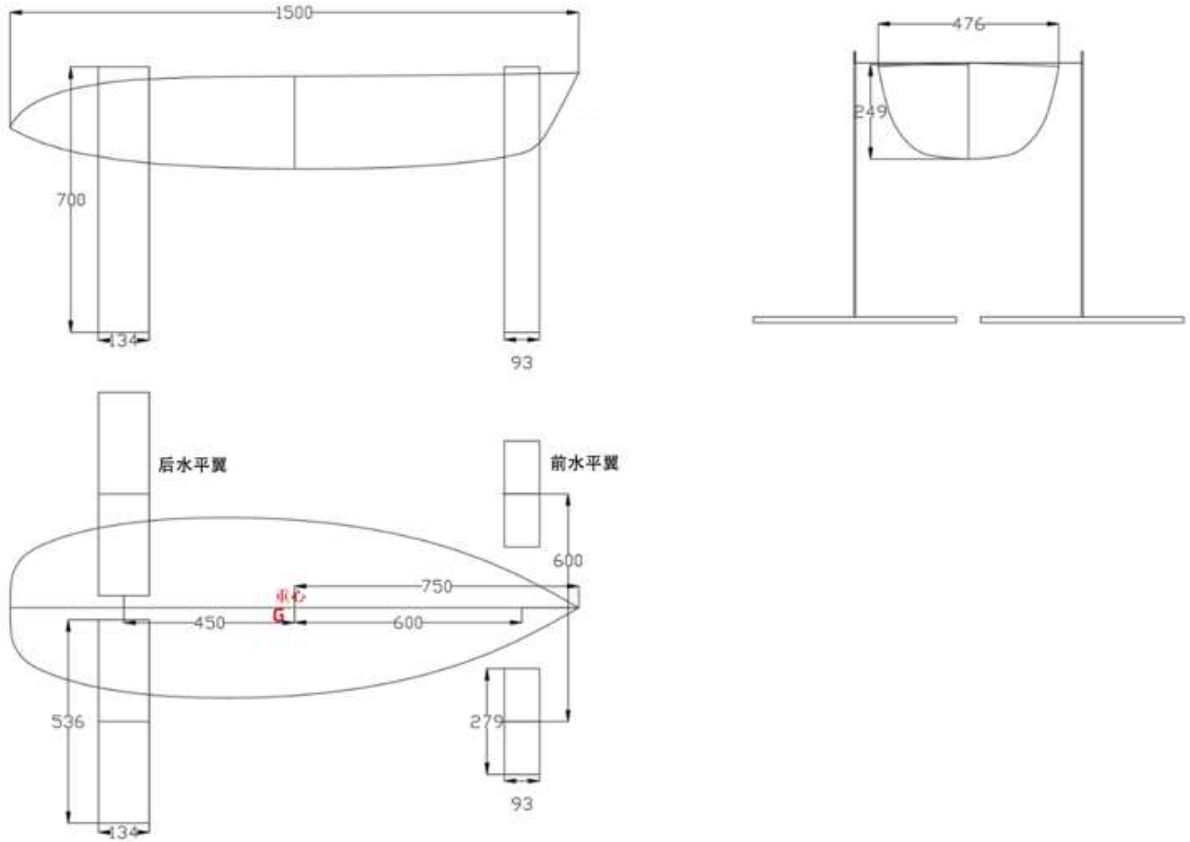
翼航仿真为主，起飞过程的控制研究较少

缺乏对风浪干扰要素和增强控制手段的研究，难以应对恶劣海况下的安全起飞要求

本文研究内容：

- 引入重物移动系统作为增强控制手段
- 翼航状态的仿真模拟
- 起飞过程的航行试验

2.1 案例船主尺度参数



2.2 重物移动系统控制原理

$$I'_{xx}\ddot{\phi}+2N\dot{\phi}+W\left|\dot{\phi}\right|\dot{\phi}+Dh\phi=M_s+M_e$$

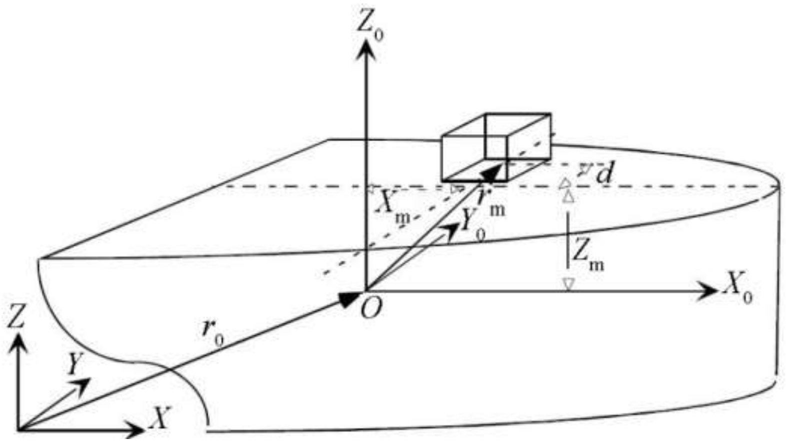
环境干扰力矩

$$M_s=z_m\cdot(mg\sin\phi+m\ddot{d}(t)-mz_m\ddot{\phi})-d(t)\cdot(mg\cos\phi+md(t)\cdot\ddot{\phi}-2m\cdot\dot{d}(t)\cdot\dot{\phi})$$

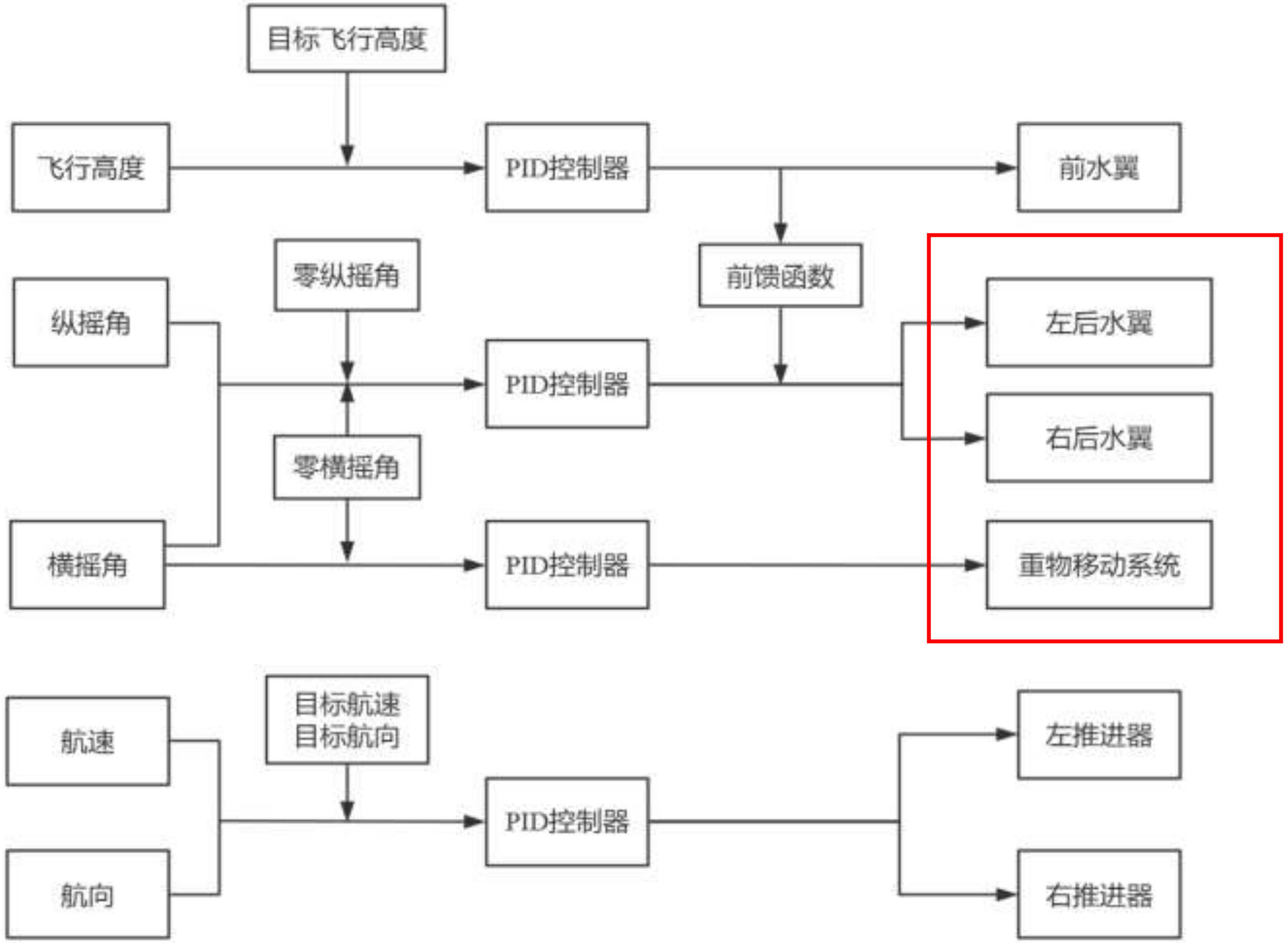
重物减摇力矩

惯性力

重物重力



2.3 飞行控制原理



$$e_\phi = \phi_d - \phi$$

$$y_f = k_{fp} e_\phi + k_{fi} \int_0^t e_\phi + k_{fd} \dot{e}_\phi$$

$$y_m = k_{mp} e_\phi + k_{mi} \int_0^t e_\phi + k_{md} \dot{e}_\phi$$

3.1 动力学模型

3.1.1 运动学和动力学方程

运动学方程：

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta & 0 & 0 & 0 \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi & 0 & 0 & 0 \\ -s\theta & c\theta s\phi & c\theta c\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & s\phi t\theta & c\phi t\theta \\ 0 & 0 & 0 & 0 & c\phi & -s\phi \\ 0 & 0 & 0 & 0 & s\phi / c\theta & c\phi / c\theta \end{pmatrix} \begin{pmatrix} u \\ v \\ w \\ p \\ q \\ r \end{pmatrix}$$

动力学方程：$M\dot{V} + CV = F$

- T型水翼
- 推进器
- 风载荷
- 重物移动系统
- 船体重力

3.1.2 T型水翼力学模型

$$V_f=\begin{pmatrix}V_{fu}\\V_{fv}\\V_{fw}\end{pmatrix}=-\begin{pmatrix}u\\v\\w\end{pmatrix}-\begin{pmatrix}q(c_{42}\cos\lambda-h_1)-rb_4\\-p(c_{42}\cos\lambda-h_1)-r(c_{41}-c_{42}\sin\lambda)\\q(c_{41}-c_{42}\sin\lambda)+pb_4\end{pmatrix}$$

$$F_{Lf}=0.5C_{Lf}(\alpha_f)\rho_w(V_{fu}{}^2+V_{fw}{}^2)S_f \qquad \alpha_f=\beta_f+\lambda+\pi$$

$$F_{Df}=0.5C_{Df}(\alpha_f)\rho_w(V_{fu}{}^2+V_{fw}{}^2)S_f \qquad \beta_f=\arctan 2(V_{fw},V_{fu})$$

$$X_f=-F_{Lf}\sin\beta_f+F_{Df}\cos\beta_f$$

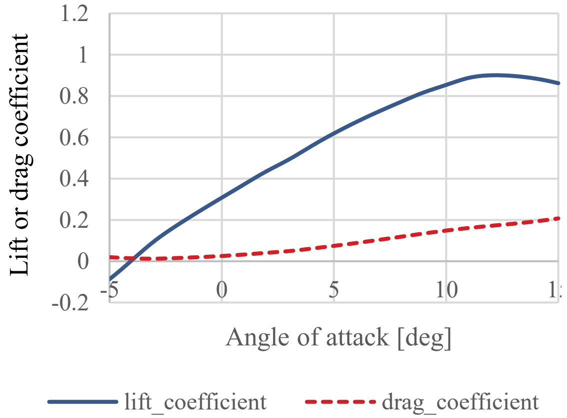
$$Y_f=0$$

$$Z_f=F_{Lf}\cos\beta_f+F_{Df}\sin\beta_f$$

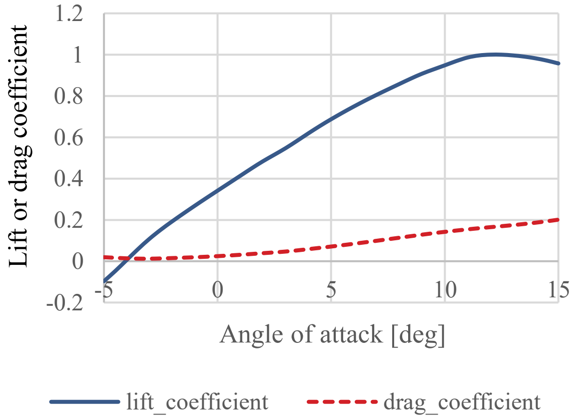
$$K_f=Z_f b_4$$

$$M_f=Z_f(c_{41}-c_{42}\sin\lambda)+X_f(c_{42}\cos\lambda-h_1)$$

$$N_f=-X_f b_4$$



前水平翼升阻力系数曲线

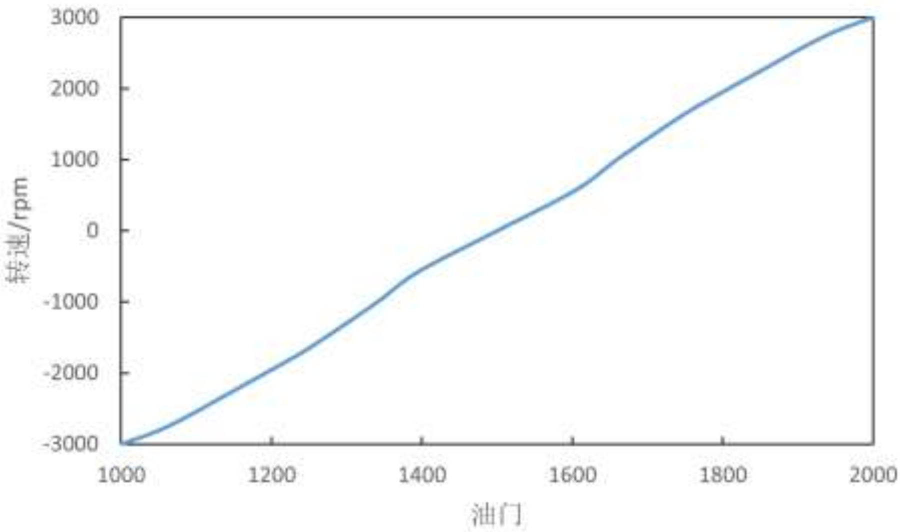


后水平翼升阻力系数曲线

3.1 动力学模型

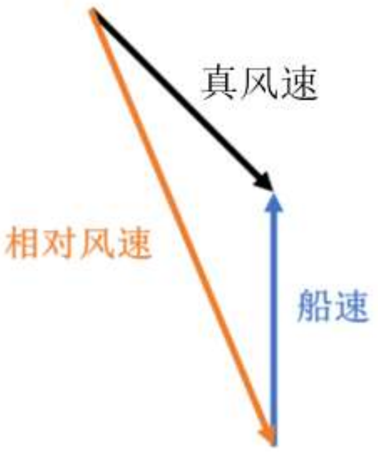
3.1.3 推进器性能模型

$$T = T_{max}(\frac{n}{n_{max}})^2$$



$$X_p = T$$
$$Y_P = 0$$
$$Z_P = 0$$
$$K_P = 0$$
$$M_P = Th_t$$
$$N_P = -Tb_t$$

3.1.4 风载荷模型



$$V_{awx} = tws \cdot \cos(twa + \beta)$$
$$V_{awy} = tws \cdot \sin(twa + \beta)$$

$$\beta = \arctan 2(v, u)$$

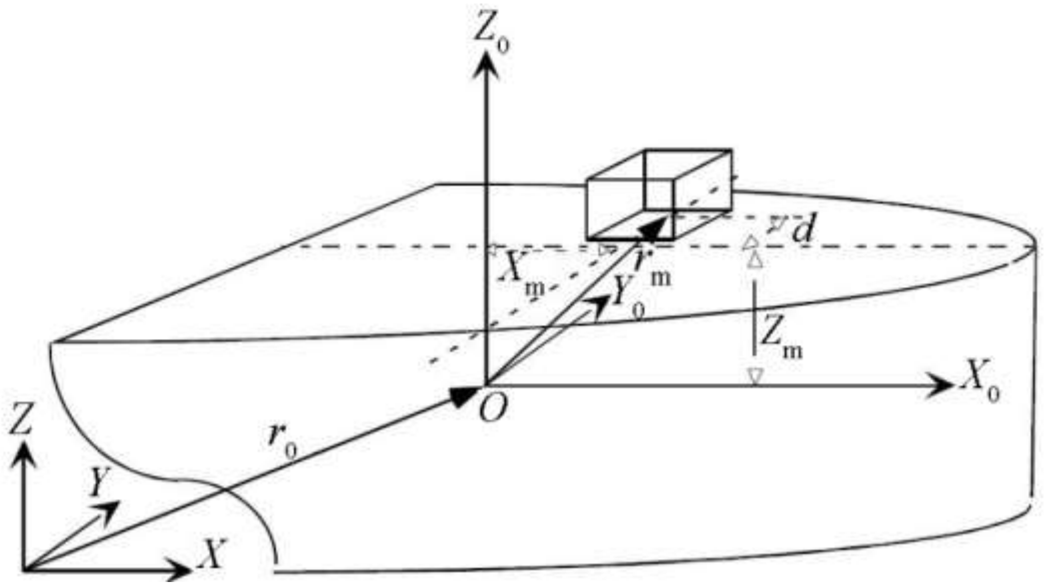
$$\alpha_{aw} = \arctan 2(-V_{awy}, -V_{awx})$$

$$X_w = 0.5 C_{wx}(\alpha_{aw}) \rho_a V_{aw}^2 S_x$$
$$Y_w = 0.5 C_{wy}(\alpha_{aw}) \rho_a V_{aw}^2 S_y$$
$$Z_w = 0$$
$$K_w = Y_w z_w$$
$$M_w = X_w z_w$$
$$N_w = 0.5 C_{wn}(\alpha_{aw}) \rho_a V_{aw}^2 S_y l_{pp}$$

α_{aw}/°	C_{wx}	C_{wy}	C_{wn}
0	0.80	0	0
10	0.81	0.09	-0.016
20	0.76	0.31	-0.007
30	0.80	0.51	-0.005
40	0.72	0.66	-0.002
50	0.59	0.76	0.008
60	0.39	0.86	0.032
70	0.08	0.90	0.047
80	-0.05	0.91	0.071
90	-0.09	0.92	0.108
100	-0.11	0.96	0.131
110	-0.17	0.97	0.162
120	-0.24	0.95	0.172
130	-0.34	0.84	0.161
140	-0.42	0.76	0.160
150	-0.49	0.60	0.150
160	-0.50	0.40	0.111
170	-0.56	0.21	0.060
180	-0.55	0	0

3.1 动力学模型

3.1.5 重物移动系统力学模型



$$X_m = m(g_x - \dot{u} - qw + rv + 2r\dot{d} - \dot{q}z_m + \dot{r}d - qpd + q^2 x_m - rpz_m)$$

$$Y_m = m(g_y - \dot{v} - ru + pw - \ddot{d} - \dot{r}x_m + \dot{p}z_m - rpz_m + r^2 d + p^2 d - pqx_m)$$

$$Z_m = m(g_z - \dot{w} - pv + qu - 2p\dot{d} - \dot{p}d + \dot{q}x_m - rpx_m + p^2 z_m + q^2 z_m - rqd)$$

$$K_m = Z_m d - Y_m z_m$$

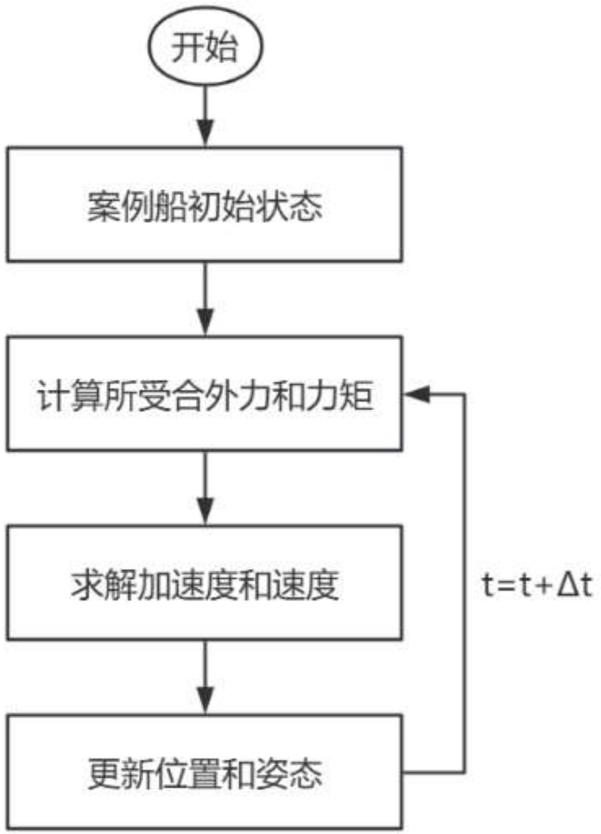
$$M_m = X_m z_m - Z_m x_m$$

$$N_m = Y_m x_m - X_m y_m$$

重物运动假设 $\begin{cases} \ddot{d} = \pm a_{\max}, 0 \\ |\dot{d}| \le v_{\max} \\ |d| \le d_{\max} \end{cases}$

只有d是控制变量!

3.2 仿真模拟方案



	工况1	工况2	工况3	工况4	工况5	工况6
航速(m/s)	2.6					
飞行高度(m)	0.25					
a_{max}(m/s²)	8					
v_{max}(m/s)	0.6					
d_{max}(mm)	150					
后水翼摆动角度差上限(°)	6					
重物质量(kg)	0.8			2.2		
海况条件	常规海况	恶劣海况	恶劣海况	常规海况	恶劣海况	恶劣海况
是否开启重物移动控制	否	否	是	否	是	否

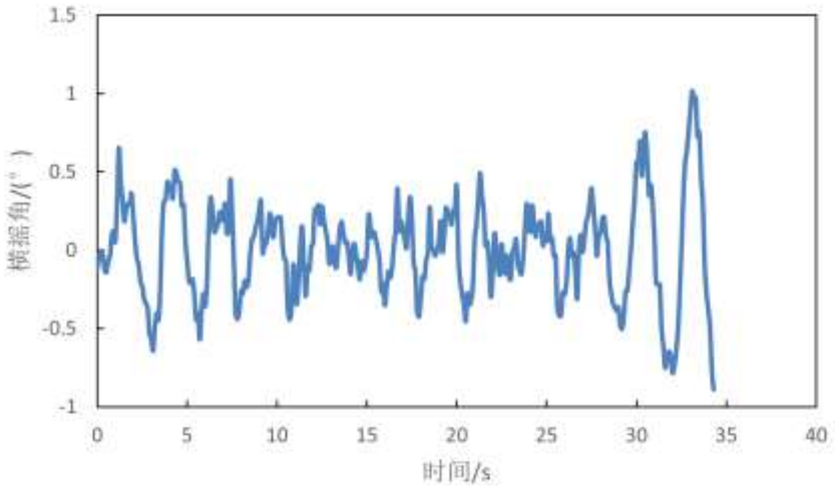
常规海况： 风载荷为零

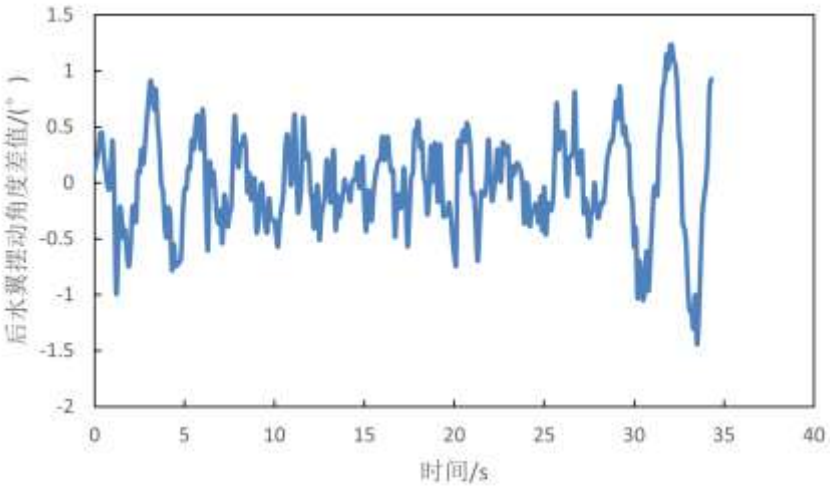
恶劣海况： $tws = 13.8 + 2.76\sin(0.2\pi t)$

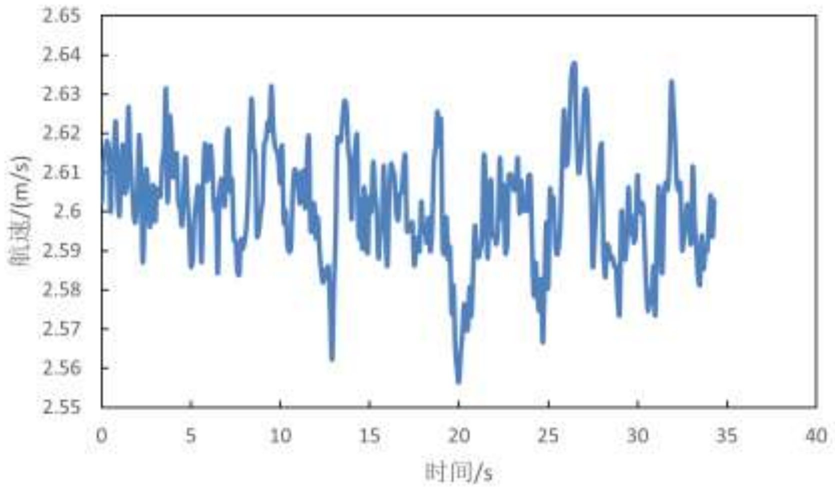
$twa = 90$

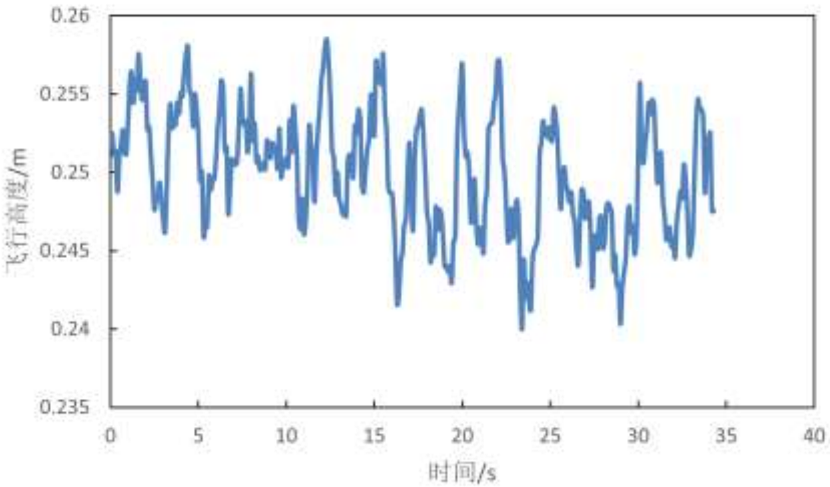
3.3 仿真模拟结果

工况1



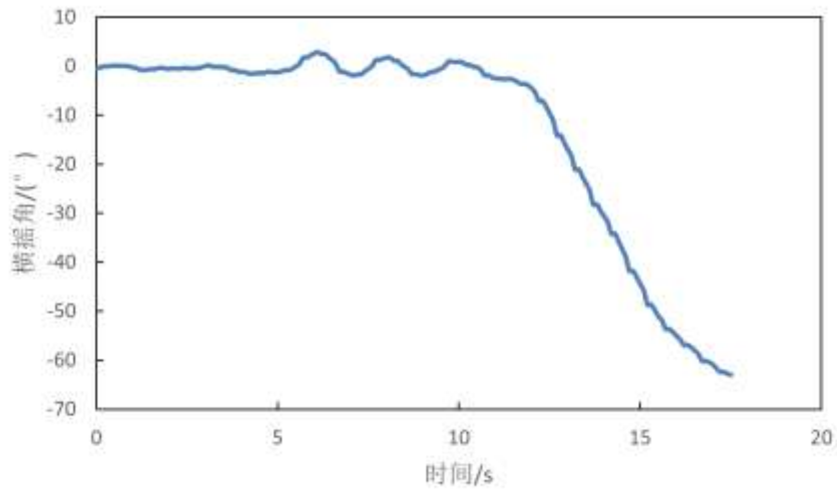


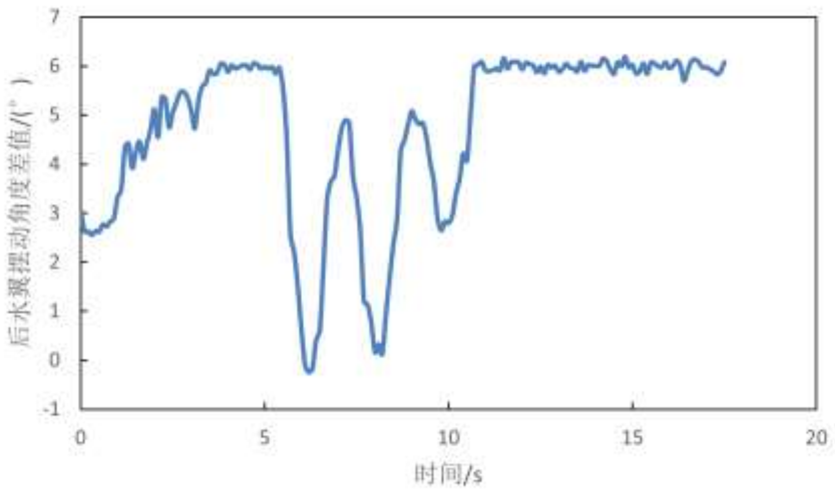


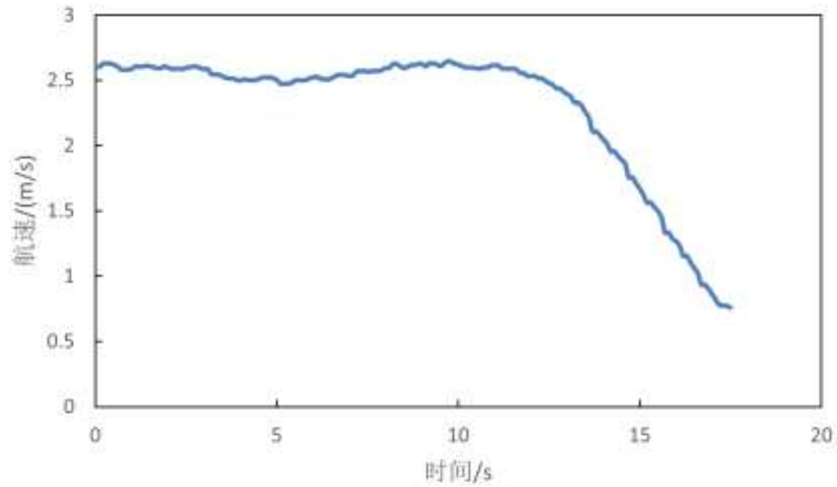


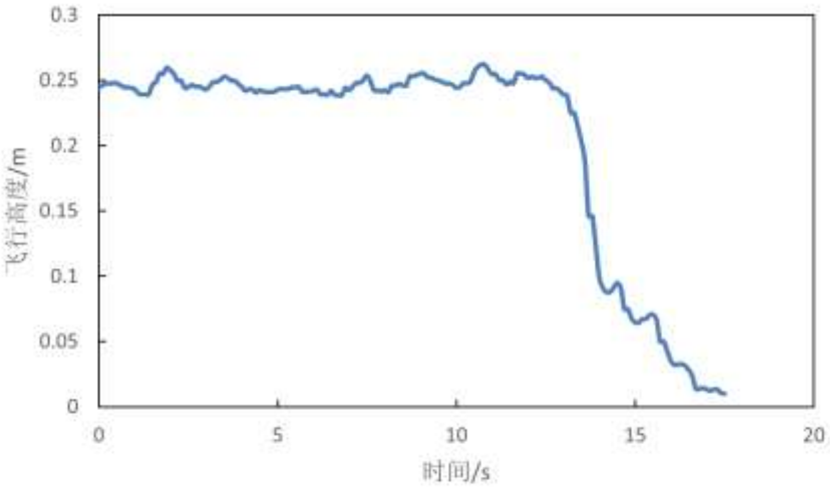
3.3 仿真模拟结果

工况2



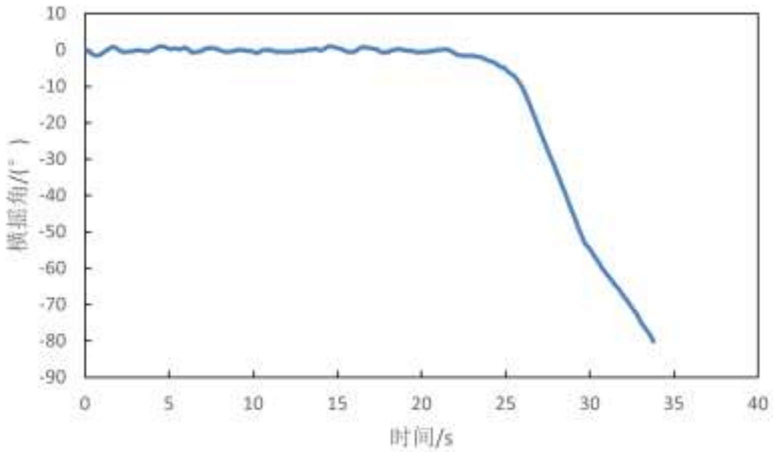


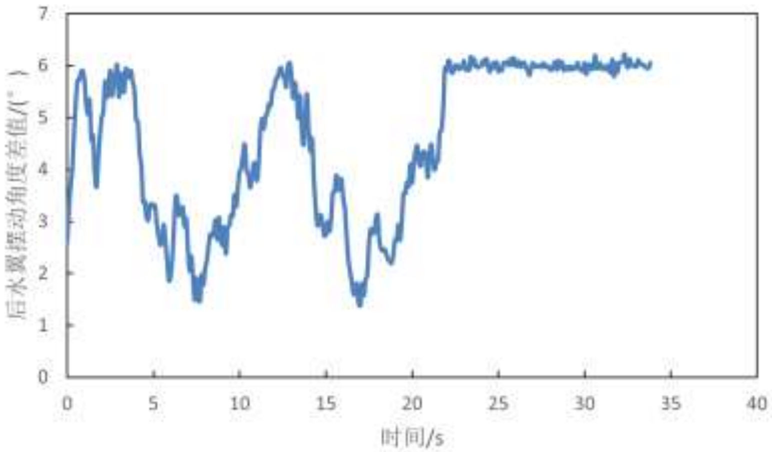


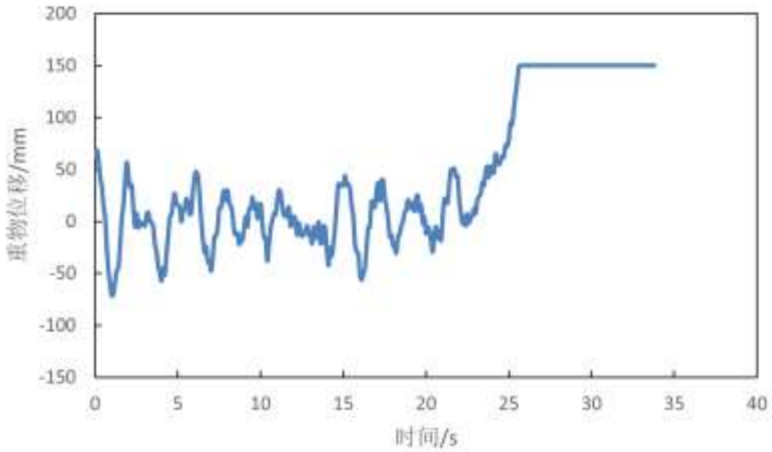


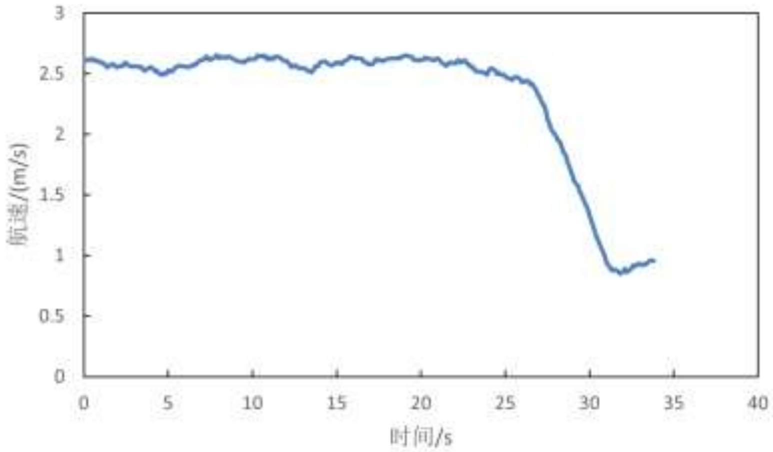
3.3 仿真模拟结果

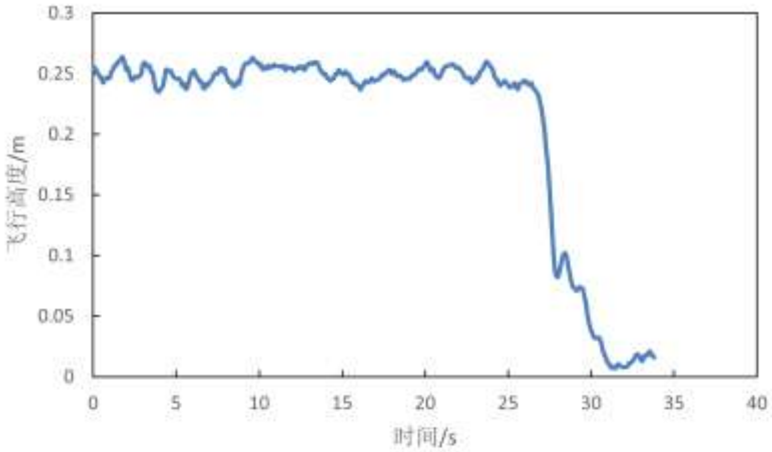
工况3





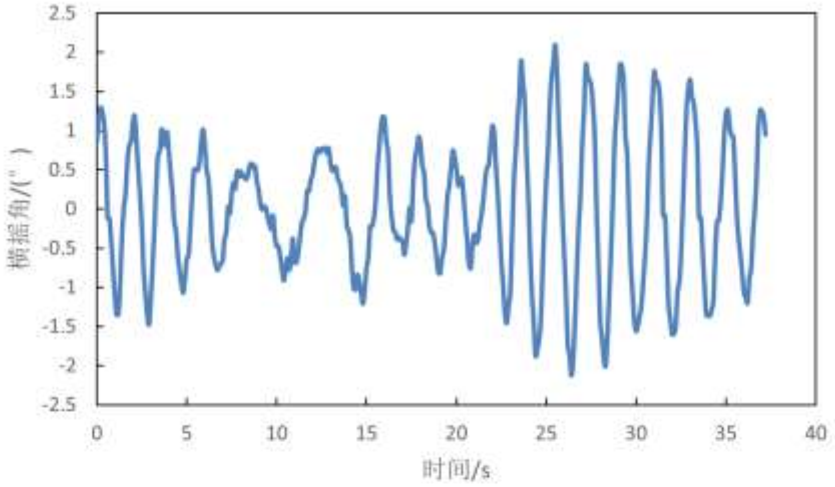


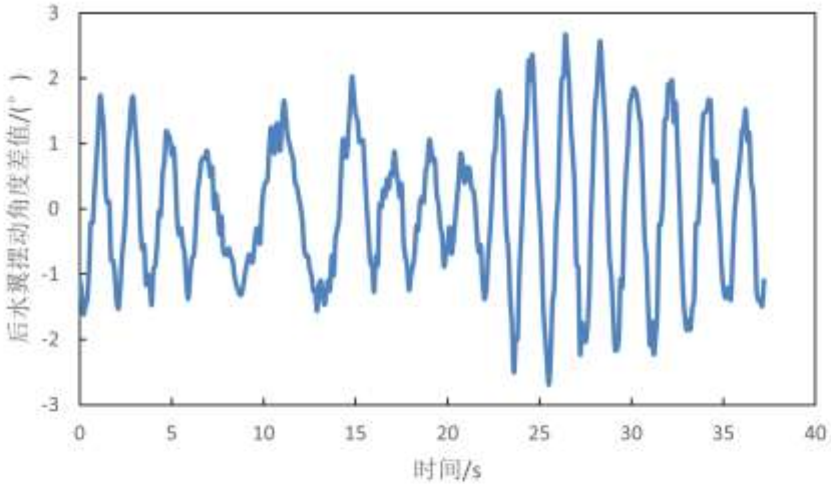


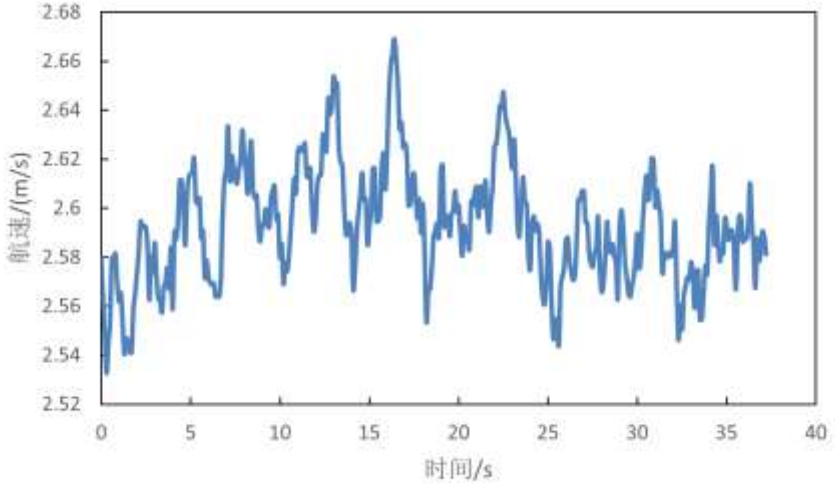


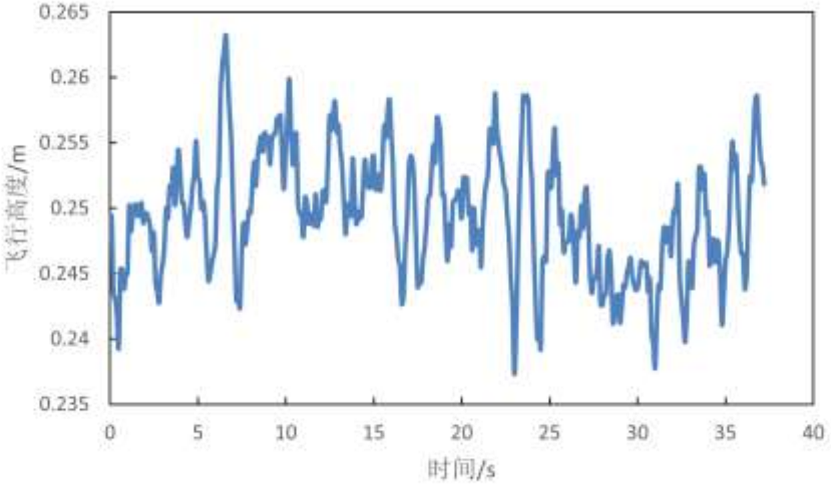
3.3 仿真模拟结果

工况4



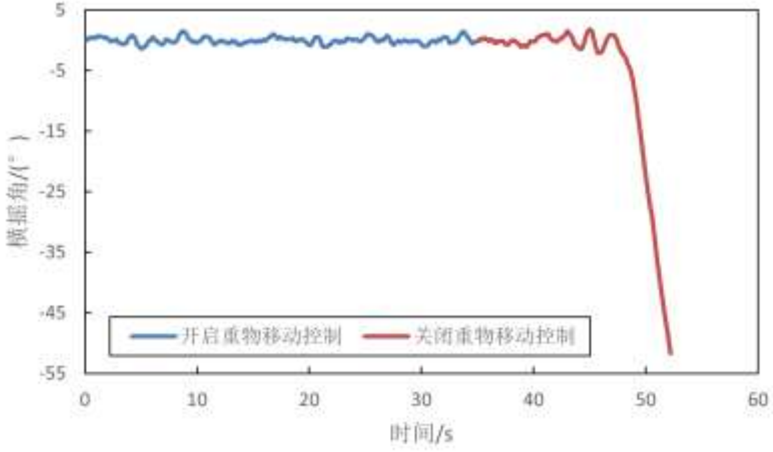


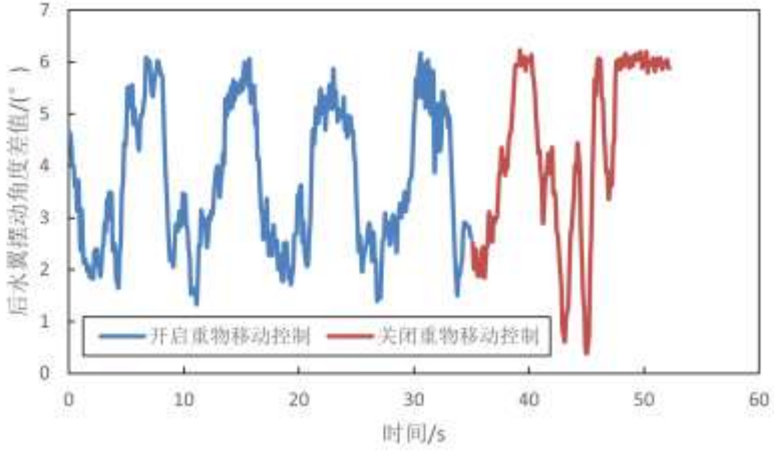


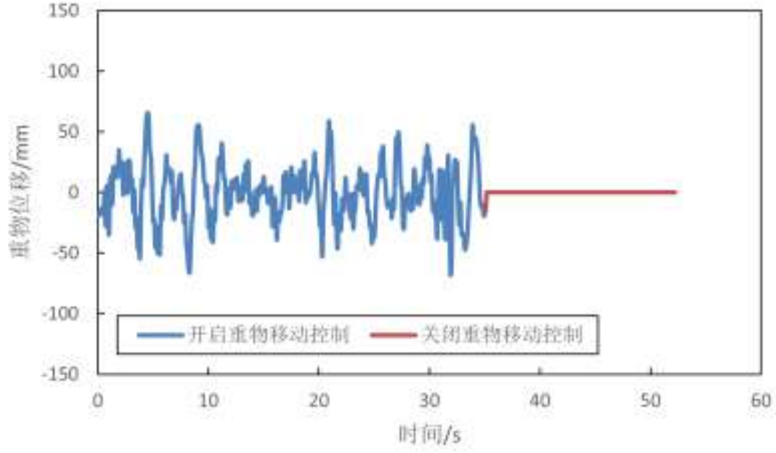


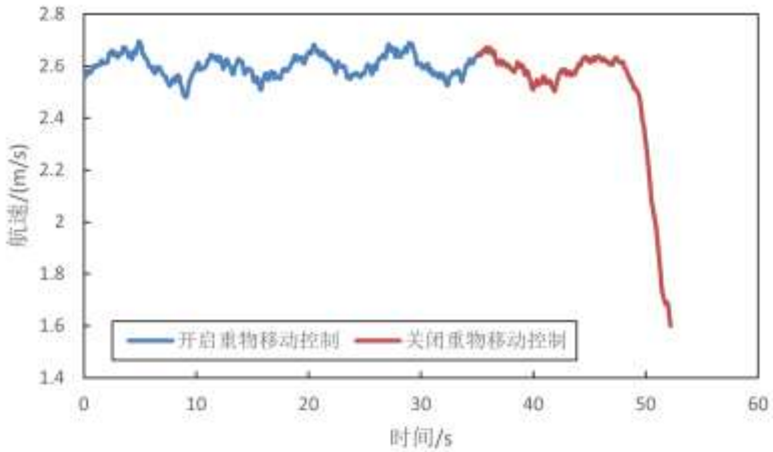
3.3 仿真模拟结果

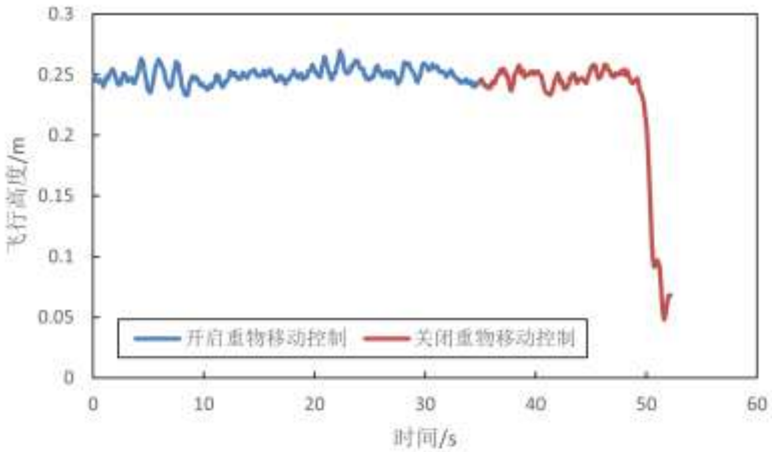
工况5和工况6







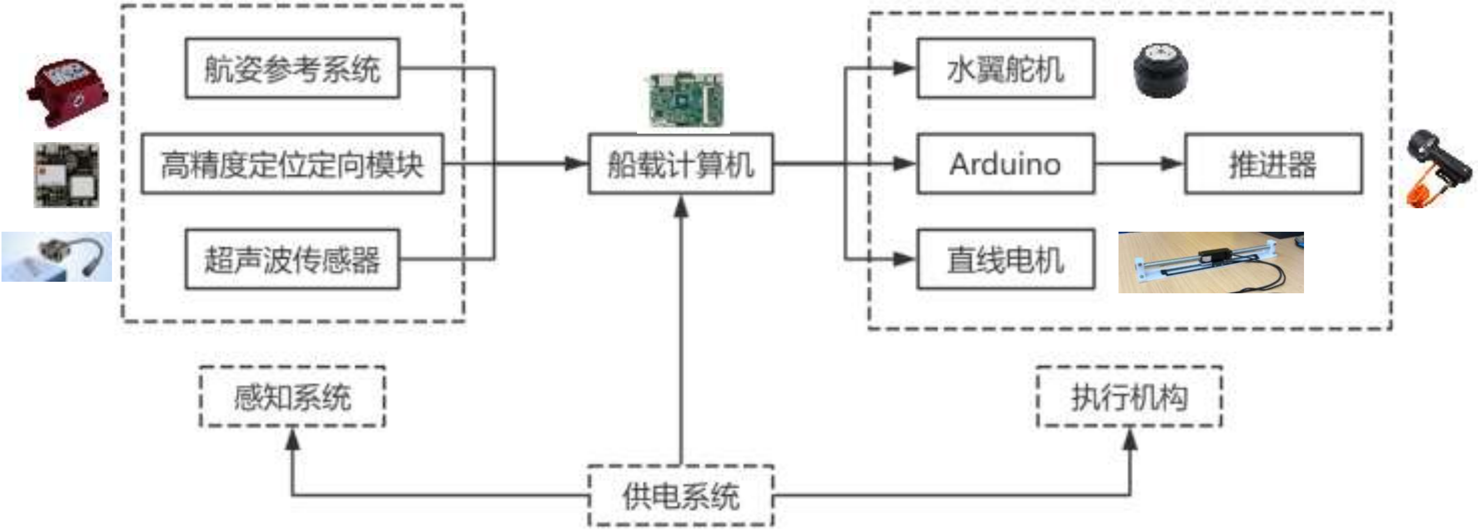




4.1 航行控制系统

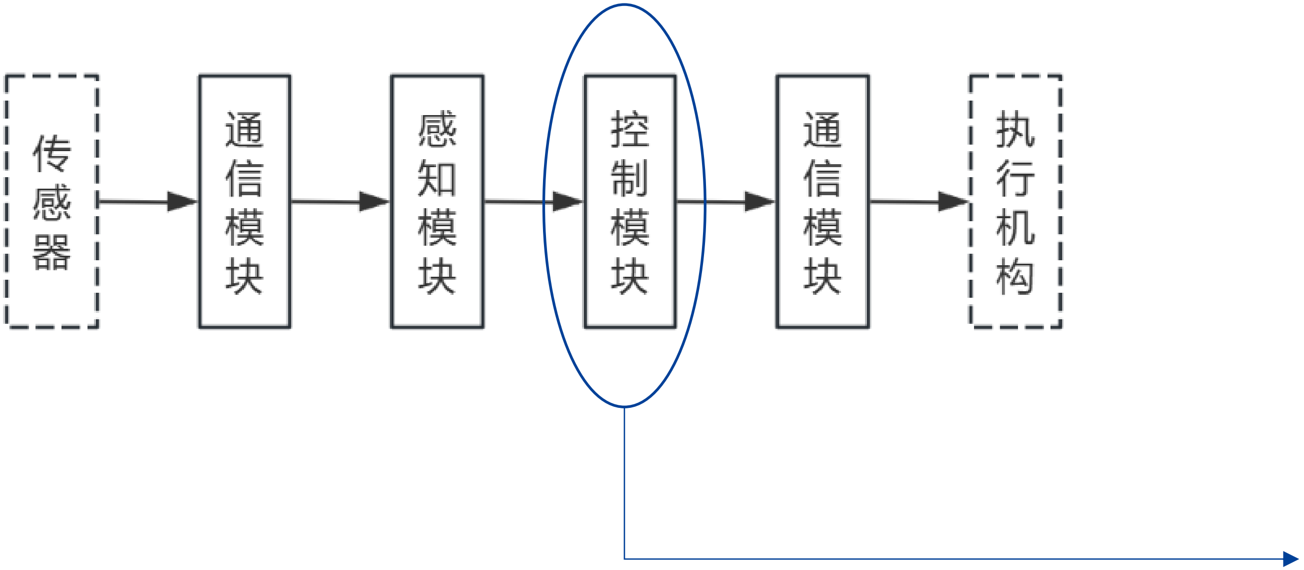
4.1.1 硬件系统

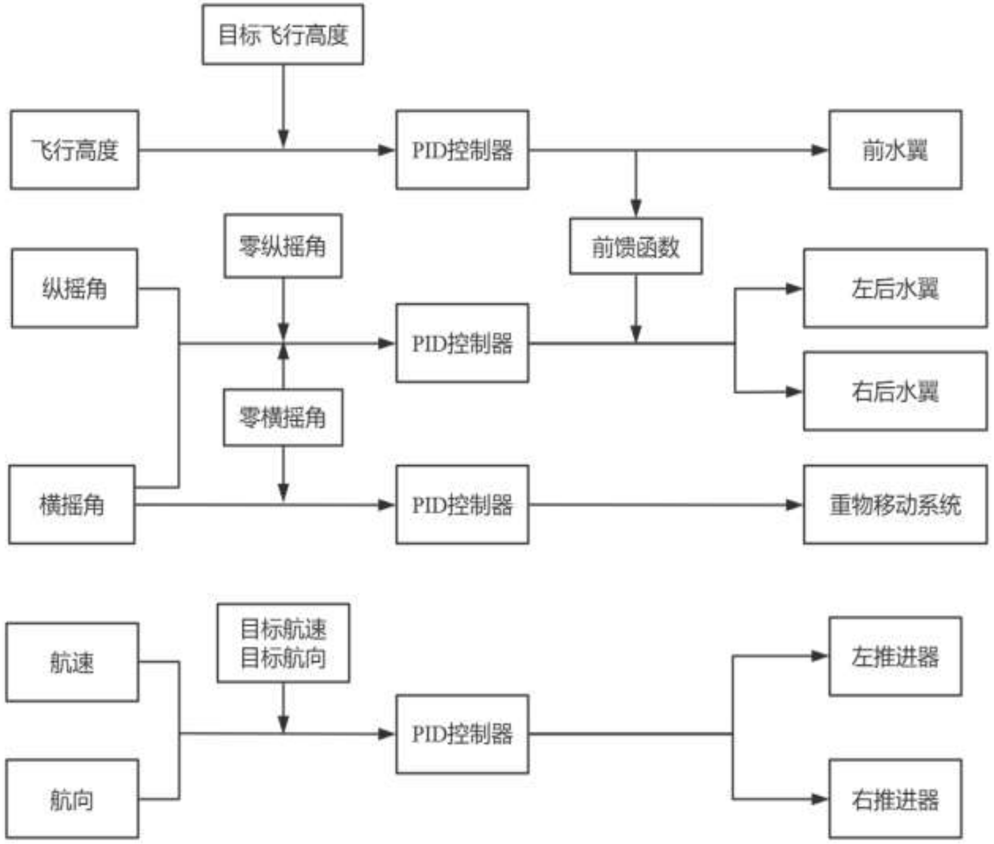
直线电机（重物移动系统）



4.1 航行控制系统

4.1.2 软件系统





整个软件系统以10 Hz的频率运行

4.2 试验方案

试验地点：上海交通大学致远湖

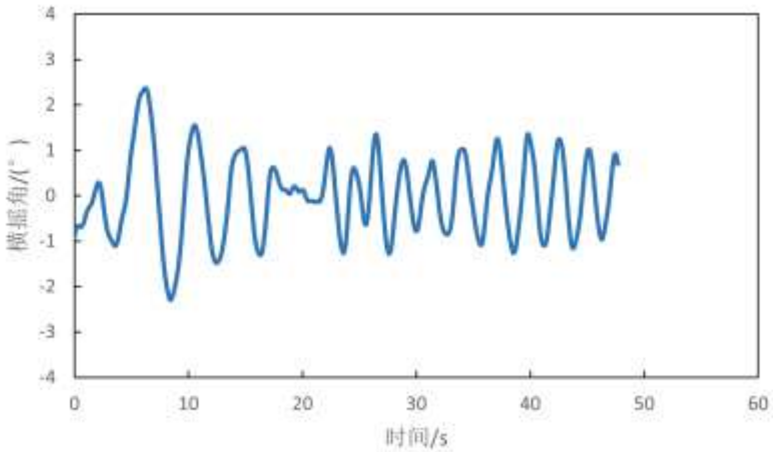
<table>
<tr><th></th><th>工况1</th><th>工况2</th><th>工况3</th><th>工况4</th><th>工况5</th><th>工况6</th></tr>
<tr><td>航速(m/s)</td><td colspan="6">2.6</td></tr>
<tr><td>飞行高度(m)</td><td colspan="6">0.25</td></tr>
<tr><td>$a_{max}(m/s^2)$</td><td colspan="6">8</td></tr>
<tr><td>$v_{max}(m/s)$</td><td colspan="6">0.6</td></tr>
<tr><td>$d_{max}(mm)$</td><td colspan="6">150</td></tr>
<tr><td>重物质量(kg)</td><td colspan="6">2.2</td></tr>
<tr><td>航向(°)</td><td>120</td><td>-60</td><td colspan="2">120</td><td colspan="2">-60</td></tr>
<tr><td>海况条件</td><td colspan="2">常规海况</td><td colspan="4">恶劣海况</td></tr>
<tr><td>是否开启重物移动控制</td><td>否</td><td>否</td><td>否</td><td>是</td><td>否</td><td>是</td></tr>
</table>

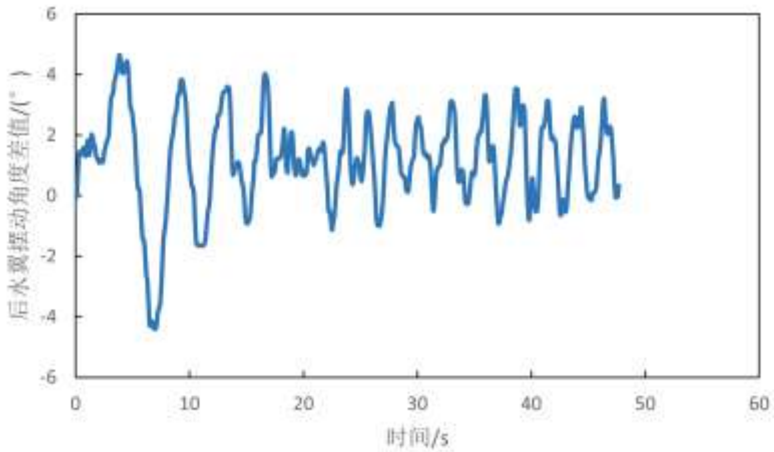
常规海况：后水翼的摆动角度差上限5°

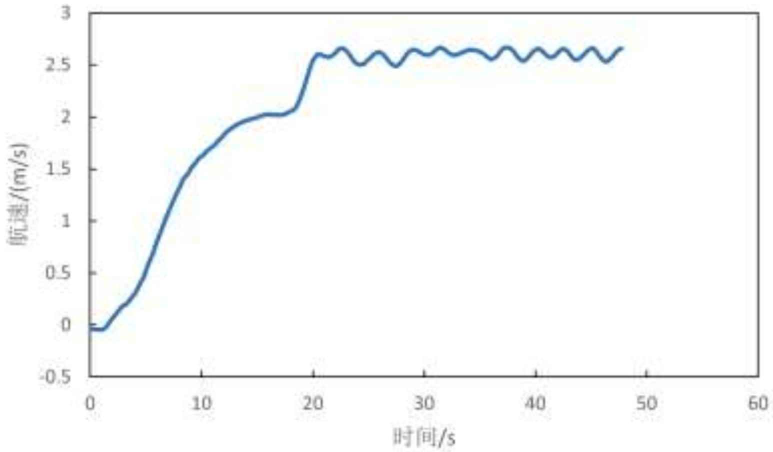
恶劣海况：后水翼的摆动角度差上限3.4°

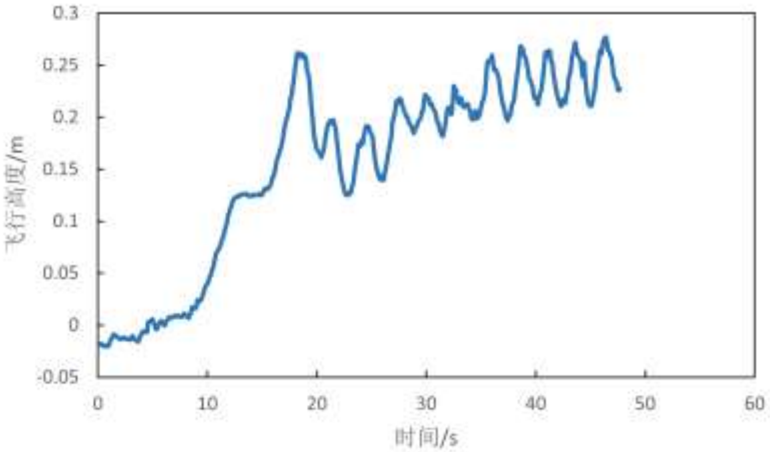
4.3 航行试验结果

工况1

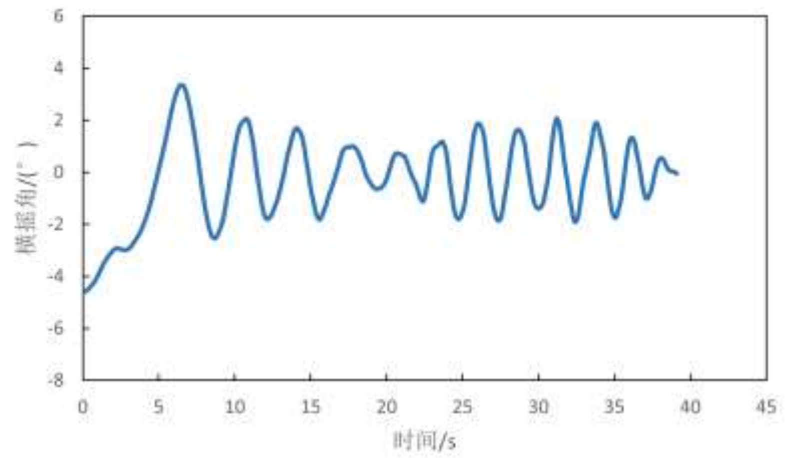


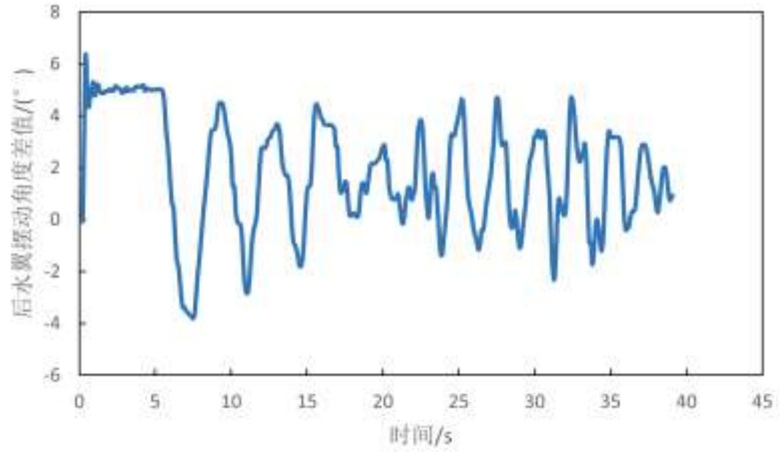


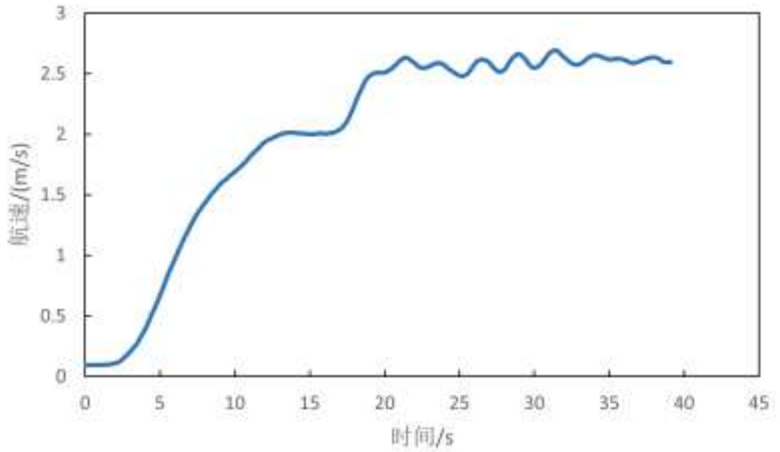


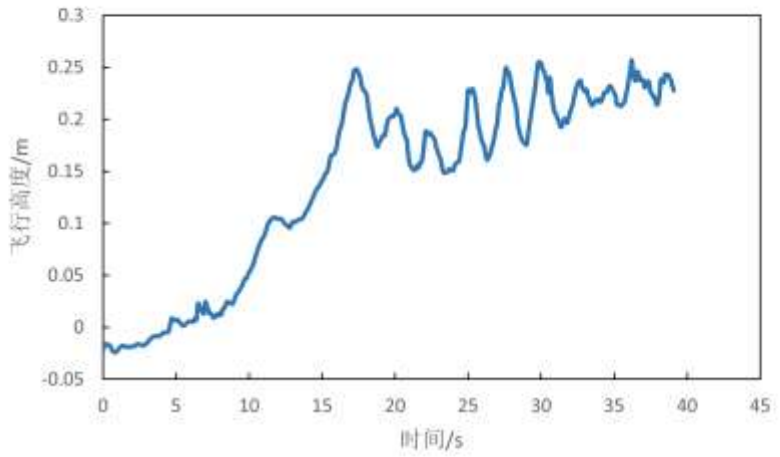


工况2









4.3 航行试验结果

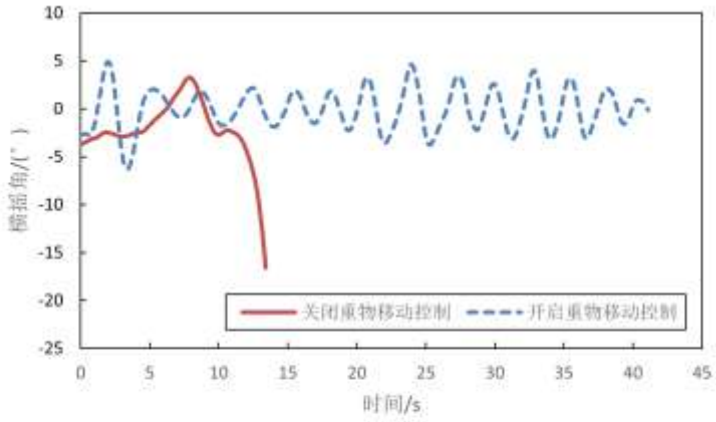
工况3和工况4

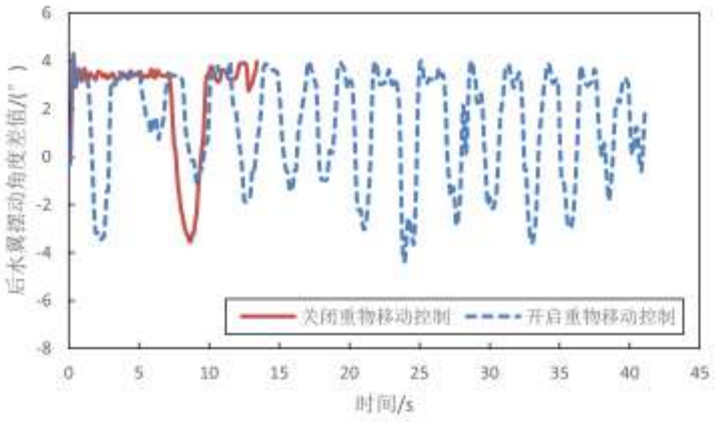
工况3：

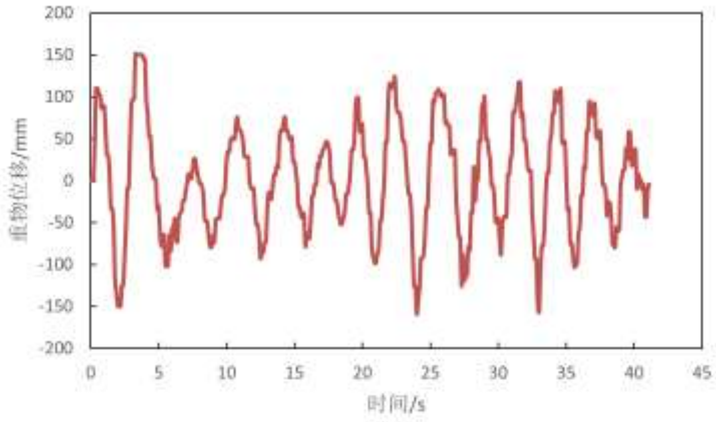
工况4：

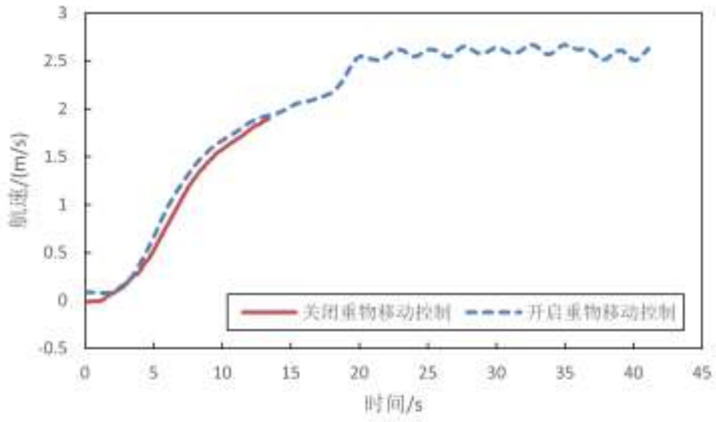
4.3 航行试验结果

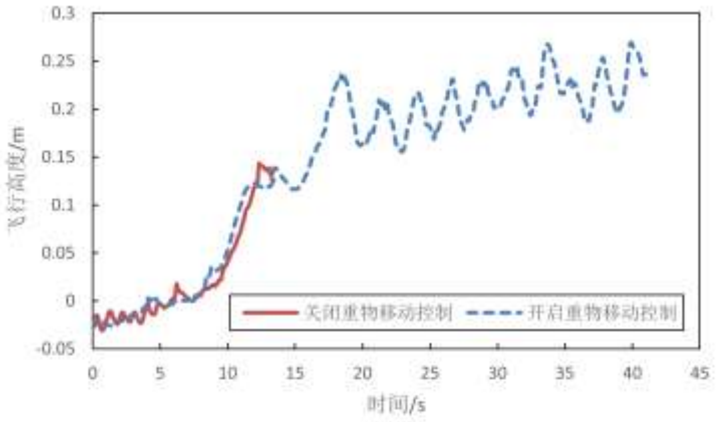
工况3和工况4











4.3 航行试验结果

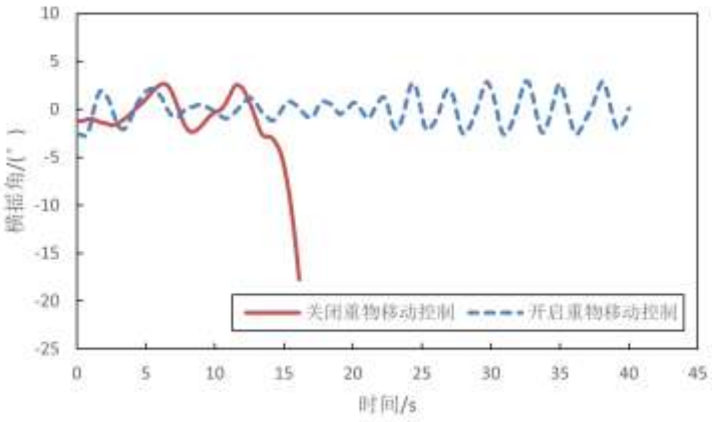
工况5和工况6

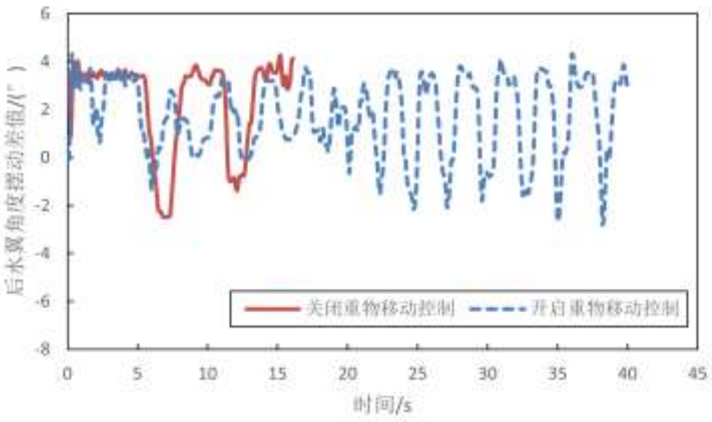
工况5：

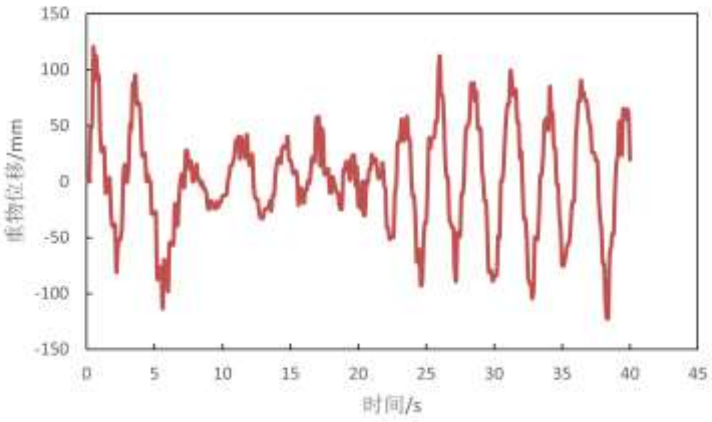
工况6：

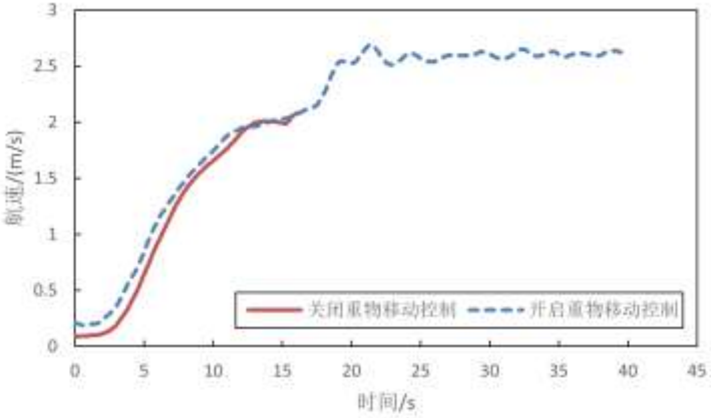
4.3 航行试验结果

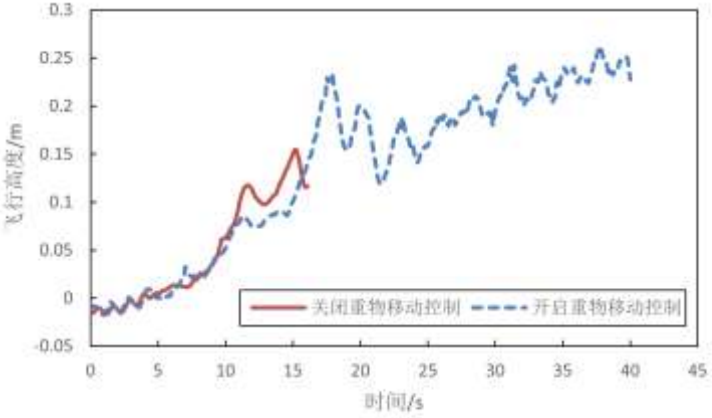
工况5和工况6











谢谢！

汇报人：王睿哲

2025年7月2日