Simulation of transverse movement of tugboat without wind and waves

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Abstract. The operation of berthing and unberthing large liquefied gas vessels, the operation of offshore berthing and unberthing rescue, the positioning of drilling platforms and other projects all require the assistance of Azimuth Stern Drive (ASD) tugboats. Traversing maneuver is one of the most important maneuvers of ASD tugboat. The process of traversing is unstable, complicated and easy to be interfered by the outside world. It is prone to tail flick and other dangerous situations. On the basis of previous studies, this paper uses the "Liangang 21" tugboat to carry out simulation experiments, realizes the tug's lateral movement control, and gives the relationship between the engine speed, propeller deflection angle and lateral movement. It is of great practical significance to the actual operation of the ASD tugboat and to improving the safety of offshore operations.

1. Introduction
With the increasing of modern marine transportation equipment, some operations such as berthing and unberthing of large liquefied gas ships, maritime search and rescue, and offshore engineering need the assistance of ASD (Azimuth Stern Drive) tugboat (called tugboat below). At present, the power of tugboat is increasing day by day to meet the use needs. Its advantages are high horsepower and sufficient power, but its shortcomings bring new challenges to the safety in operation, which requires the tugboat to operate more accurately. Some scholars have given the simulation model of tugboats, but usually aiming at the assistance of large ships, the manoeuvring of tugboats is often simplified, which makes the handling characteristics of tugboats unclear. Therefore, in order to ensure the safety of tugboat operation and understand the maneuverability characteristics of tugboats, it is very necessary to study the maneuverability of tugboats. Traversing is one of the most complex operation methods in tugboat operation, which plays a vital role in the successful completion of offshore operations. Therefore, it is necessary to study the characteristics of traversing through simulation experiments.

2. The mathematical model of the motion of the ASD tugboat
There are two mathematical models of ship motion: integral model and separated model. In this paper, the MMG (Maneuvering Modeling Group) model with three degrees of freedom is adopted, and according to the coordinate system in Figure 1, the tugboat mathematical model is established as shown in equation (1).
In equation (1), $x$, $y$, and $n$ are external forces acting on $x$ and $y$ and moments around $z$ axis respectively, and subscripts $H$ and $P$ are acting forces of bare hull and propeller respectively. $u$, $v$, and $r$ are the longitudinal and transverse velocity components and steering angular velocity of the ship respectively; $\delta$, $\psi$ and $\beta$ are propeller deflection angle, heading angle and drift angle respectively. $m_x$ and $m_y$ are the longitudinal and transverse additional masses of the ship; $J_{zz}$ and $I_{zz}$ are the additional mass moment of inertia and mass moment of inertia of the ship around $Z_0$ axis, respectively, and $x_C$ is the coordinate value of the ship on $x$ axis in the attached coordinate system.

3. Calculation of external force on hull

3.1. Calculation of fluid force of bare hull

Hydrodynamic calculation models are quite different in different environments and operating modes. There is no unified model under multiple working conditions, so it is necessary to select the optimal model from the existing mathematical models. In this paper, the method proposed by Yang (Jia and Yang, 1999) is adopted to meet the working conditions of the tugboat in the constant speed range and the low speed range. When the drift angle $\beta \leq 20^\circ$, Inoue's model is adopted. Yoshimura's model is adopted when drift angle $\beta \geq 30^\circ$. When the drift angle is $20^\circ \leq \beta \leq 30^\circ$, the interpolation between them is adopted.

Inoue's model:

$$X_H = X(u) + X_n v^2 + X_y vr + X_{nr} r^2$$
$$Y_H = Y_v + Y_r + Y_{v|r} v r + Y_{v^2|r} v^2 r$$
$$N_H = N_v + N_r + N_{v|r} v r + N_{v^2|r} v^2 r$$

Yoshimura's model:

$$X_H = X(u) + X_n v^2 + X_y vr + X_{nr} r^2$$
$$Y_H = Y_v + Y_r + Y_{v|r} v r + Y_{v^2|r} v^2 r + N_{v^2|r} v^2 r$$

In equation (2), $X(u)$, $X_n$, $X_y$, and $X_{nr}$ are the longitudinal hydrodynamic factors; $Y_v$, $Y_r$, $N_v$, and $N_r$ are the linear viscous hydrodynamic factors; $Y_{v|r}$, $Y_{v^2|r}$, $N_{v|r}$, $N_{v^2|r}$, and $N_{v^2|r}$ are nonlinear hydrodynamic factors, which are obtained by the calculation method in reference (Jia and Yang, 1999).
\[ X_H = X_H(r=0) + X_{\nu} + X_{\nu} r^2 \]
\[ Y_H = Y_H(r=0) + Y_{\nu} |v| + \frac{1}{2} \rho d C_{\text{d}}(L + C_{\nu} x) v + C_{\nu} x |v| \, dx \]
\[ N_H = N_H(r=0) + N_{\nu} |v| - \frac{1}{2} \rho d C_{\text{d}}(L + C_{\nu} x) v + C_{\nu} x |v| \, dx \]

In equation (3), \( \rho \) is the density of seawater; \( D \) is draught; \( L \) is the molded length; \( C_d \) is the transverse flow resistance coefficient of hull; \( C_{\nu} \) and \( C_{\nu} \) are model's correction coefficients; \( X_H(r=0) \), \( Y_H(r=0) \), and \( N_H(r=0) \) are the hydrodynamic forces and moments when the first angular velocity is \( r=0 \) in the low speed range; reference (Yang and Yu, 1998) for calculating other hydrodynamic derivatives. The variable step-size compound Simpson method is used to calculate the integral, and the analytical solution is unstable in computer simulation, and the calculation time is long. Using the variable step-size compound Simpson formula to obtain the numerical solution meets the requirements in accuracy, and the calculation speed is fast, so the simulation process is not easy to diverge.

### 3.2. Calculation of propeller force

The main power of the ASD tugboats comes from the thrust generated by two propellers which can rotate 360 degrees. The tugboat is operated by adjusting the rotating speed and deflection angle of the propellers, as shown in Figure 2. The calculation model of propeller thrust is shown in equation (4).

\[ T = (1-t_p) \rho n^2 D_p^5 k_T(J_p) \]
\[ Q_p = \rho n^2 D_p^5 k_Q(J_p) \]
\[ J_p = (1-w_p)u / nD_p \]

In equation (4), \( t_p \) is the thrust derating coefficient, and the thrust derating coefficient is treated as a constant according to the method in reference (Li, 2007). \( T \) is the propeller thrust; \( n \) is the revolution rate of propeller; \( D_p \) is the paddle diameter; \( k_T(J_p) \) is the thrust coefficient; \( k_Q(J_p) \) is the torque coefficient; \( J_p \) is the propeller speed coefficient; \( Q_p \) is torque absorbed by propeller; \( w_p \) is the wake coefficient.

The propeller combined thrust and torque model is shown in equation (5)

\[ X_p = T_p \cos(\delta_p) + T_s \cos(\delta_s) \]
\[ Y_p = T_p \sin(\delta_p) + T_s \sin(\delta_s) \]
\[ N_p = [T_p \cos(\delta_p) - T_s \cos(\delta_s)] \cdot \frac{1}{2} L_{ps} - Y_p \cdot L_{OP} \]

In equation (5), \( \delta \) is propeller deflection angle (0° in stern direction and 0°-360° in clockwise direction), and \( T \) is propeller thrust, subscripts \( p \) and \( s \) represent port and starboard propellers respectively; \( L_{ps} \) is the distance between two propellers; \( L_{OP} \) is the longitudinal position of the propeller.
4. Simulation
In order to verify the effectiveness of the mathematical model, take the ASD tugboat "Liangang 21" as the simulation plant of interest, Python is used for the simulation, and the parameters of "Liangang 21" are shown in Table 1.

Table 1. Parameters for "Liangang 21"

| Parameter                        | Value   |
|----------------------------------|---------|
| Designed waterline length $L_w$ (m) | 32.3    |
| Length between perpendiculars $L$ (m) | 29.0    |
| Breadth (molded) $B$ (m)         | 9.8     |
| Forward draft $d_f$ (m)          | 2.48    |
| After draft $d_a$ (m)            | 3.88    |
| Block coefficient $C_b$          | 0.566   |

4.1. Turning test
According to the published data of "Liangang 21", the initial speed is 13.6kn, and the engine revolution is 720rpm. Figure 3 shows the comparison results between the tugboat trial and the simulation experiment. Table 2 shows the comparison results of main data between the tugboat trial and the simulation experiment. According to the accuracy of the ship model described by equation (6), $\eta$ is 94.5%. To sum up, the coincidence of turning cycle is good.

$$\eta = \frac{\min(D_s, D_r)}{\max(D_s, D_r)} \times 100\%$$  \hspace{1cm} (6)

In which $D_s$ is the diameter of simulated cycle; $D_r$ is the tactical diameter of the tugboat trial; $\eta$ is conformity function.
Table 2. Turning test results.

|                  | Simulation | Tugboat trial | Error |
|------------------|------------|---------------|-------|
| engine revolution(rpm) | 720.0      | 720.0         | 0     |
| Paddle angle(°)    | 315        | 315           | 0     |
| Maximum advance(m) | 50.5       | 45.3          | 11.5% |
| Maximum transfer(m)| 59.3       | 62.3          | 4.8%  |
| Tactical diameter(m)| 57.8       | 61.9          | 6.6%  |
| Final diameter(m)  | 56.9       | 60.2          | 5.5%  |

Figure 4 shows the simulation turning test (Zhang and Zhang, 2016) under different initial speeds. The initial speeds are 3kn, 6kn, 9kn, and 13.6kn respectively. Other initial parameters are consistent with previous turning test, and the corresponding maximum advance are 55.8m, 56.5m, 57.5m, and 59.3m respectively, and the maximum transfer are 32.7m, 35.2m, and 32.7m respectively. The diameter of the cycle is basically unchanged, which is consistent with the statement in reference (Hong, 2016) that the ship speed has little influence on the cycle, which partly verifies the validity of the model in the low speed range.

To sum up, the comparison between real ship experiment and simulation experiment data meets the engineering application standard, which shows that the mathematical model of tugboat is reasonable in constant speed domain and low speed domain.

4.2. Simulation of Transversal Manoeuvring

Usually, when the tugboat moves transversely, it is in a state where there is no longitudinal speed or the longitudinal speed is very small, and most of the tugboat moves transversely in the low speed range. Therefore, the established model is used for transverse operation to study the characteristics of the tugboat. According to the transversal manoeuvring method proposed in reference (Ma, 2002), taking the left traverse as an example, the simulation experiment was carried out when the initial course of the tug was 0° and the longitudinal speed was 0.01 m/s.
4.2.1. Transverse movement when the revolution rate of the engine is constant and the propeller angles change. The revolution rate of the port and the starboard engine is 350rpm, the transverse movement simulation of propellers at different angles are carried out. The propeller angles are shown in Table 3, and the motion trajectory is shown in Figure 5.

Table 3. Propeller angles of simulation.

| Port propeller angle (°) | 240 | 230 | 220 | 210 |
|--------------------------|-----|-----|-----|-----|
| Starboard propeller angle (°) | 300 | 310 | 320 | 330 |

Figure 5. Transversing motion trajectory on unchanged revolution.

It can be seen from the experiment that when the revolution of the engines is constant, the port propeller angle goes to 180° (dead ahead) and the starboard propeller goes to 360° (dead astern), it is easier to keep the transversing state. When the port and starboard propellers are 188° and 351° respectively, they can basically keep the transversing situation.

4.2.2. Transversal movement when the revolution of the engines changes and the propeller angles remain unchanged. Figure 6 shows the transversing trajectory at different revolution (engine revolution rate are 350rpm, 500rpm, 650rpm and 720rpm, respectively) when the port and starboard propellers are 188° and 351° respectively, and the corresponding transversing speeds are 0.53kn, 0.75kn, 0.99kn, and 1.1kn.

Figure 6. Transversing motion trajectory on changed revolution.
To sum up, when the engine revolution is increased and other experimental conditions are the same, the tugboat movement situation is basically consistent with the previous, while the transverse speed basically increases proportionally, which shows that the engine revolution has little influence on the traverse situation when the propeller angles are fixed, but only on the transverse speed.

5. Conclusions
In this paper, aiming at some practical situations of tugboat operation, a three-degrees-of-freedom tugboat mathematical model combining constant speed domain and low speed domain is put forward, which truly reflects the tug’s transversing movement when there is no wind or wave. Through transversing simulation experiment, it is found that the engine revolution rate and propeller angle respectively influence the transversing situation and speed, which realizes the verification of tug's transversing characteristics by theoretical and simulation experimental data, and is not limited to the premise of simulation experiment, which is convenient for subsequent research on the influence of wind, current, wave, and shallow water correction on transversing.

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