Dynamic Characteristics Analysis of the Rigid Flexible Coupling Multi-body System of Wharf-cable-dynamic Positioning Vessel

Dapeng Zhang1,*, Yong Bai1, a, Keqiang Zhu2, b and Jian Liu2, c
1College of Civil Engineering Architecture, Zhejiang University, Hangzhou, China
2Faculty of Maritime and Transportation, Ningbo University, Beijing, China
*Corresponding author e-mail: zhangdapengzju@163.com, a1214265737@qq.com, bzhukeqiang@nbu.edu.cn, c275645569@qq.com

Abstract. In order to study the coupling effect of the rigid-flexible multi-body system composed of the dynamic positioning vessel, the wharf and mooring cables in mooring state, the lumped mass method was applied to discretize the mooring cables into lumped mass models for the calculation of the mooring tension of the mooring system, the nonlinear reaction force of dock fenders was simulated by Link unit in Orca Flex, and the thrust allocation of thrusters was based on PID control system. The full coupling dynamic time-frequency characteristics of the multi-body system has been analysed. The results show that the performance of the side thruster and vessel’s positioning capability can be improved effectively when the target position is selected reasonably.

1. Introduction
Aalbers and Merchant [1] made a hydrodynamic model testing for a closed loop DP assisted mooring system. The dynamic response of the unloading condition of a shuttle oil tanker under the action of the dynamic positioning system was studied by Tannuri [2]. Wichers and Van [3] have done some researches on the application of the mooring assisted dynamic positioning system of a deepwater FPSO, and improved the design idea of the dynamic auxiliary mooring location system. New methods and requirements were proposed for the design of the mooring assisted aided dynamic positioning of a FPSO by Sorensen et al. [4].

At present, there are few studies on the coupling response of the dynamic positioning vessel-wharf-mooring cable under the berthing state. Based on the calculation results of hydrodynamic performance of the system, the time-frequency characteristics of the wharf-cable-dynamic positioning vessel system with the combined action of mooring cable restoring force and side thrust under different wave directions are obtained. Some suggestions are put forward, which are of certain guiding significance to improve the safety of the mooring assisted dynamic positioning system and reduce the coupling vibration of each degree of freedom of the whole system.
2. Theory for Dynamic Positioning Vessel in the Berthing State with Mooring Cables

2.1. Wave theory
In engineering, the Stokes 5th wave theory proposed by Skjelbreia and Hendrickson is often used as a reference. Therefore, the Stokes 5th wave theory based on power series expansion of $kH/2$ given by Fenton [5] is adopted in this paper, as it is more accurate than the former method.

2.2. Time domain coupled motion equation for dynamic positioning vessel
The time domain coupling equation of dynamic positioning vessel can be shown as follows:

$$\begin{align*}
\{[M] + [a_{ij}]}\{\ddot{x}_j\} + \int_{-\infty}^{t} \{\dot{x}_j\} \left[R_y(t-\tau)\right] d\tau + \{C_y\}\{x_j\} = \{F_{wj}(t)\} + \sum_{k=1}^{n} \left[F_{mk}(t) + F_c(t) + F_{wind}(t)\right] + \left[F_{DP}(t)\right] + \left[F_T(t)\right]
\end{align*}$$

(1)

Where, $M$ is the vessel mass, $a_{ij}$ is the added mass matrix, $R_y$ is the time-memory function which is defined as:

$$R_y(t) = \frac{2}{\pi} \int_{0}^{\pi} B_y(\omega) \frac{\sin \omega t}{\omega} d\omega$$

$B_y$ is the damping.
$C_y$ is the restoring force determined by the vessel and mooring system stiffness.
$F_{wj}$ is the wave force, including the first order and second order components.
$F_{mk}$ is the mooring force defined by the mooring cables.
$F_c$ and $F_{wind}$ are the current and wind forces, respectively.
$F_{DP}$ is the total thrust of the thrusters based on PID dynamic allocation algorithm.
$F_T$ is the total collision force between the ship and the wharf.
$F_m$ and $F_T$ reflect the effect of the combined force of the collision force of the wharf and the mooring force of mooring cables on the dynamic positioning vessel.

2.3. Dynamic positioning PID control
Because of the flexibility of Python in handling data types, we design Python interface as a wrapper to access the internal functions of Orca Flex Dll, which can better improve program performance.

The control system compares the sway, surge, and yaw of the DP Vessel with the target value through an external function.

$$F_{x,y} = f(e_{x,y})$$

(2)

$$F_z = f(e_{\theta})$$

(3)

$$f(e_{x,y,\theta}) = K_p e_x + K_i \int e_x dt + K_d \frac{de_x}{dt} + F_w(a_w,v_w)$$

(4)

$F_{x,y}$ is the restoring resultant force which contains the longitudinal restoring force $F_x$ of the vessel’s surge motion and the lateral restoring force $F_y$ of the vessel's sway motion; $F_z$ is the restoring moment of the ship's yaw motion; $e_x$ is the difference between the surge and the target value; $e_y$ is the difference between the sway and the target value; $e_{\theta}$ is the difference between the yaw angle and the target value; $K_p$ is the proportional gain, $K_i$ is the integral gain, $K_d$ is the differential gain, $a_w$ is the wind angle, $v_w$ is the wind speed, $F_w$ is the force or moment of the wind acting on the vessel.
2.4. Calculation of collision force between the vessel and wharf
Since the vessel model is treated as a rigid body in OrcaFlex, it is necessary to cover the vessel hull with a layer of elastic solid to calculate the collision force between the vessel and the wharf, then the corresponding impact force is calculated according to the deformation of the elastic solid.

\[ F_c = KA_c d \]  

(5)

In equation (5): \( K \) is the normal stiffness of the elastic solid, \( kN/m^3 \); \( A_c \) is the contact area during the collision, \( m^2 \); \( d \) is the amount of deformation of the elastic-plastic solid in the vertical direction during the collision, \( m \).

2.5. The vessel wave frequency motion and RAO
For wave frequency motion, here we use the amplitude of response per unit wave amplitude, and to use the phase lag from the time the wave crest passes the RAO origin until the maximum positive excursion is reached (in other words, the phase origin being at the RAO origin). Mathematically, this is given by:

\[ x = R \cdot a \cdot \cos(\omega t - \phi) \]  

(6)

\( x \) is the vessel displacement (in length units for surge, sway, heave; in degrees for roll, pitch, yaw); \( a, \omega \) are wave amplitude (in length units) and frequency (in radians/second), respectively; \( t \) is time (in seconds); \( R, \phi \) are the RAO amplitude and phase.

2.6. The second order slow-drift force
In this paper, we used the hydrodynamic software AQWA to obtain the RAO and the 2nd order wave transfer function QTFs, then imported them into OrcaFlex.

3. The Calculation Model of the Rigid Flexible Coupling Multi-body System of Wharf-Cable-Dynamic Positioning Vessel in OrcaFlex

| Table 1. Parameters of the dynamic positioning vessel |
|-----------------------------------------------|
| \( L_{pp} / m \) | Breadth/ m | Moulded depth/m | Draught/ m | Transverse GM /m | Longitudinal GM /m | \( \Delta/t \) | Surge area/m \(^2\) | Sway area/m \(^2\) | Block coefficient | Yaw moment of inertia Mz/kg·m \(^2\) |
|----------------|-----------|----------------|-----------|-----------------|-------------------|--------|----------------|---------------|----------------|----------------|
| 103            | 16        | 13.3           | 6.66      | 1.84            | 114               | 880    | 191            | 927           | 0.804          | 5.83×10\(^9\) |

The model of wharf-cable-dynamic positioning vessel is shown in Figure1. And the vessel without a DP system in this paper also has the same parameters in Table 1.
The mooring tension of the mooring lines is calculated by the lumped mass method. This is the mathematical basis for establishing the model of the mooring lines in this paper [6]. The parameters of each mooring line: the inner diameter is 0.25 m; the outer diameter is 0.35 m; the bending stiffness is 120 kN·m²; the axial stiffness is 700000 kN; the torsional stiffness is 80 kN·m²; the line density is 0.18 t/m; the Poisson’s ratio is 0.5; the length is 17 m.

4. Numerical Results and Analysis

**Table 2. Environmental load parameters**

| Wave height/ (m) | Wave period/(s) | Current velocity/(m/s) | Wind speed/(m/s) | Direction/(°) |
|------------------|-----------------|------------------------|------------------|---------------|
| 3                | 12              | 2.46                   | 3                | 180(in negative x direction) |

4.1. **Comparison of numerical results between the non-dynamic positioning vessel under mooring state and dynamic positioning vessel under mooring state**

The target position of the dynamic positioning vessel in Fig. 2 is (67.5, 95). It can be found that the position and the yaw angle fluctuation of the dynamic positioning vessel are very small. Since the non-dynamic position vessel is not constrained by the vessel's thruster, its motion range is larger in the horizontal three degrees of freedom and the coupling effect between different degrees of freedom is significantly higher than that of the dynamic positioning vessel under mooring state.
It can be seen that in Fig. 3 the spectral density of the horizontal degrees of freedom of the dynamic positioning vessel is smaller than that of the non-dynamic positioning vessel. In X axis direction, the three peaks of the sway spectral density of the non-dynamic positioning vessel increases, the low-frequency peaks of the non-dynamic positioning vessel are mainly distributed at 0.02 Hz and 0.04 Hz. In the direction of Y axis, the spectral density of the non-dynamic positioning vessel’s surge is far higher than that in the direction of X axis, and it reaches the peak at 0.025 Hz.

In time domain, the mooring tension at the end of Mooring Line 4 shows an irregular drastic change trend. This change increases the possibility of the breakage of the mooring line due to the sudden change of tension. During the stage of 0-800s, just as shown in Figures 2 and 3, the horizontal three degrees of freedom motion of the dynamic positioning vessel is maintained within a very small range, which indicates that the irregular motion of the vessel at horizontal three degrees of freedom can be transformed into regular change of mooring tension in time domain by lateral thrust of side thruster. In frequency domain, the mooring tension spectral density at the end of Mooring Line 4 of the non-dynamic positioning vessel is uniformly distributed within the range of 0.0Hz-0.3Hz, and the frequency component of its motion is complex. In stark contrast, the peak value of the mooring tension at the end of Mooring Line 4 of the dynamic positioning vessel is located at 0.08Hz.
4.2. Comparison of numerical results between the dynamic positioning vessel with mooring lines and dynamic positioning vessel without mooring lines

![Figure 5](image)

**Figure 5.** Trajectory of vessel during t = -10s to 800s

Fig. 5(a) shows the trajectory of the dynamic positioning vessel with mooring lines in x-y plane, its target position is (67.5, 95). And it illustrates that the vessel is finally stabilized at (67.5±0.05, 95±0.003). Fig. 5(b) also shows the trajectory of the dynamic positioning vessel with mooring lines in x-y plane, but its target position is (64, 95). The trajectory of the dynamic positioning vessel without mooring lines in x-y plane is shown in Fig. 5(c), its target position is (67.5, 95), and it finally stabilizes at (67.5±2.9, 95±0.09).

![Figure 6](image)

**Figure 6.** Curves of vessel’s yaw angle in time domain

Fig. 6 shows the curves of the yaw angle of the dynamic positioning vessel (with mooring lines and without mooring lines) in time domain under the same environmental loads. TP (., .) indicates the target position of the dynamic positioning vessel in x-y plane.
Figure 7. Mooring tension and its spectral density of Mooring Line 4 of the dynamic vessel with mooring lines

Compared to the non-dynamic positioning vessel with mooring lines in Fig. 4, the sudden change of tension at the end of Mooring Line 4 of the dynamic positioning vessel with mooring lines (TP (64, 95)) is relieved to a certain extent, but it can be seen that the distribution of the curves of the spectral density of the mooring tension at the end of Mooring Line 4 still occupies a relatively large frequency range. Therefore, the reasonable target position can guarantee the peak value of the mooring tension spectral density is near the wave external load frequency.

5. Conclusion

The conclusions are as follows:

1) In the mooring state, the degree of coupling between the degrees of freedom of the non-dynamic positioning vessel is larger, the spectral density of the horizontal three degrees of freedom in the frequency domain is higher, and the coupling between the degrees of freedom leads to the sudden change of the mooring tension in the mooring cables and the uniform distribution of the spectral density in the frequency domain. In stark contrast, due to the reaction force of the side thruster, the frequency of the mooring tension of the mooring lines is concentrated near the external wave frequency, which indicates that the pretension in the mooring lines plays a good role in absorbing the first-order wave load on the vessel and transfers the irregular motion of the dynamic positioning vessel into the regular change of the mooring tension of the mooring lines.

2) The positioning ability of the dynamic positioning vessel with mooring lines is not always better than that of the dynamic positioning vessel without mooring lines. A reasonable target position will greatly reduce the frequency of changes in the lateral thrust load and improve the work efficiency of the side thruster, it can play a positive role in improving the overall safety of the coupling system.

References

[1] Aalbers AB, Merchant AA, The hydrodynamic model testing for closed loop DP assisted mooring. Proceedings of the Offshore Technology Conference, 3-6 May, Houston, America. (1996).
[2] Tannuri EA, Saad AC, Morishita HM, Offloading operation with a DP shuttle tanker: comparison between full scale measurements and numerical simulation results. Proceedings of the 8th IFAC Conference on Manoeuvring and Control of Marine Craft, 16-18 September, Guarujá, Brazil. (2009).
[3] Wichers J, Van Dijk R, Benefits of using assisted DP for deepwater mooring system. Proceedings of the Offshore Technology Conference, 3-6 May, Houston, America. (1996).
[4] Sørensen A, Strand JP, Fossen T. I, Thruster assisted position mooring system for turret anchored FPSOs. Proceedings of the IEEE International Conference on Control Applications, 22 - 26 August, Hawaii, America. (1999).
[5] Fenton J D., A high-order cnoidal wave theory. Journal of Fluid Mechanics. 1979, pp.129 - 161.
[6] Bai Y, Zhang D, Zhu K. Dynamic analysis of umbilical cable under interference. Ships and Offshore Structures, 2018, pp.809 - 821.