Numerical Investigation of Large Nonpowered Ships Anchor Chain Mooring Force in Extreme Offshore Environment

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Abstract. Nonpowered vessels can’t self-propelled and initiative resist wind and stream. Single point buoy mooring system is one of effective ways for nonpowered vessel to mooring in extreme offshore environment. Based on wind, flow and wave model, the bow anchor mooring force model can be achieved. Through compared with physical model test data, the scientificity and rationality of the mathematical anchor chain mooring force model of single point buoy is verified [1]. Then the design of nonpowered vessel buoy engineering is analyzed by the means of single point buoy mooring system mathematical model.

1. Introduction
Nonpowered vessels can’t self-propelled and initiative resist wind and stream. Single point buoy mooring system is one of effective ways for nonpowered vessel to mooring in extreme offshore environment. Based on wind, flow and wave model, the bow anchor mooring force model can be achieved. Through compared with physical model test data, the scientificity and rationality of the mathematical anchor chain mooring force model of single point buoy is verified [1]. Then the design of nonpowered vessel buoy engineering is analyzed by the means of single point buoy mooring system mathematical model.

2. The Structure of single point buoy of large nonpowered vessels
Mooring system is composed of vessels, anchor chain (hawser), buoy, underwater anchor chain and anchor system (chart 1). The acting force on vessel from wind, wave and stream is transmitted successively through the vessel, buoy, anchor chain and anchor, which results in a static balance for the whole system in the condition of stable wind and flow and enough acting time [2].

The anchor chain is not straightly moored to the buoy, instead, it is linked with the end shackle on top of the underwater anchor chain. The downward degree of freedom of end shackle is restricted by the buoy through which the end shackle bearing tensile force can be pulled out to let the mooring force go straight to anchor system through underwater anchor chain. The force analysis of buoy mooring
system components in extreme offshore environment is foundation to study buoy and anchor selection, anchor chain requirements and anchor block design as well as secure anchoring computing and etc.

Figure 1. Single point Buoy Mooring System of Large Nonpowered Vessels.

3. Environment Load calculation Model

3.1. Wave-force Model

It can be approximately calculated using Diazole’s equation with drift force and force moment, which is as follows. [3]

\[
\begin{align*}
X_W &= \frac{1}{2} \rho g L \xi^2 C_{ XD}(\lambda) \cos(\chi) \\
Y_W &= \frac{1}{2} \rho g L \xi^2 C_{ YD}(\lambda) \sin(\chi) \\
N_W &= \frac{1}{2} \rho g L \xi^2 C_{ ND}(\lambda) \sin(\chi)
\end{align*}
\]  

(1)

In the above formula, \(X_W\), \(Y_W\), and \(N_W\) represent for longitudinal and horizontal drift force and force moment respectively, as well as \(C_{ XD}\), \(C_{ YD}\), and \(C_{ ND}\) for wave drift force, wave moment coefficient and wave length function respectively, \(\rho\) for seawater density, \(g\) for gravitational acceleration, \(L\) for ship length, \(\xi\) for wave amplitude, \(\lambda\) for wave length, \(\chi\) for wave encounter angle. Daidola showed his own empirical formulas as follow.

\[
\begin{align*}
C_{ XD}(\lambda) &= 0.05 - 0.2(\lambda / L) + 0.75(\lambda / L)^2 - 0.51(\lambda / L)^3 \\
C_{ YD}(\lambda) &= 0.46 + 6.83(\lambda / L) - 15.65(\lambda / L)^2 + 8.44(\lambda / L)^3 \\
C_{ ND}(\lambda) &= -0.11 + 0.68(\lambda / L) - 0.79(\lambda / L)^2 + 0.21(\lambda / L)^3
\end{align*}
\]  

(2)

3.2. Wind Force Acting on Ship and the Calculation of \(X_a\), \(Y_a\) and \(N_a\)

Tang zhonggu’s regression formula was used to calculate \(C_{Ra}\) (wind pressure coefficient), \(\alpha_a\) (wind pressure resultant force angle) and \(Ce\) (center coefficient of wind pressure force). Wind pressure forces, \(X_a\), \(Y_a\) and \(Na\), are as follow. [4] [5]

\[
\begin{align*}
X_a &= \frac{1}{2} \rho_a \sqrt{A_r^2 + A_l^2} \cdot \vec{V} \cdot C_{Ra} \cos \alpha a \\
Y_a &= \frac{1}{2} \rho_a \sqrt{A_r^2 + A_l^2} \cdot \vec{V} \cdot C_{Ra} \sin \alpha a \\
N_a &= L_{ma} (0.5 - C_e) Y_a
\end{align*}
\]  

(3)
**C_{Ra}** (wind pressure resultant force coefficient), **α** (wind pressure central position) and **α_a** (wind pressure resultant force angle) can be estimated in the following formula.

\[
C_{Ra} = 1.325 - 0.05 \cos 2\theta - 0.35 \cos 4\theta - 0.175 \cos 6\theta
\]

\[
\alpha/L_{oa} = 0.291 + 0.0023\theta
\]

\[
C_{e} = \frac{C_{e}}{L_{oa}} + 0.003 \left( \frac{2\rho_{a}}{\pi} - 90 \right)
\]

Here, **θ** represents for ship’s wind pressure angle, **V** for wind speed, **A_T** and **A_L** for frontal projected vessel and profile projected vessel above water line respectively, **C** for the distance between the center and headpost of profile projected vessel, **Loa** for overall ship length, **ρ_a** for air density (**1.226kg/m^3**).

### 3.3. Flow Force Acting on Ship and the Calculating of X_H, Y_H, N_H

Formulas of vessel’s dataflow during oblique sailing are as follow,

\[
X_H = \frac{1}{2} \rho L d V^2 C_x
\]

\[
Y_H = \frac{1}{2} \rho L d V^2 C_y
\]

\[
N_H = \frac{1}{2} \rho L^2 d V^2 C_n
\]

Here, **P** represents for water density (seawater **1025kg/m^3** , fresh water **1000kg/m^3**), **L** for ship length, **d** for draft, **V** for resultant velocity or relative velocity (m/s), **C_x**, **C_y** and **C_n** for dataflow coefficients which are generally expressed as the function of **β** (drift angle).

\[
C_x = X_{uw} u' u' + X_{vv} v' v' + X_{uv} u' v' + X_{uv} v' u'
\]

\[
C_y = Y_{uw} u' v' + Y_{vv} v' v' + Y_{uv} u' v' + Y_{uv} v' u'
\]

\[
C_n = N_{uw} u' u' + N_{vv} v' v' + N_{uv} u' v' + N_{uv} v' u'
\]

Therein, **u' = u/V**, **v' = v/V**, **X_{uw}** and **X_{vv}** are dimensionless quantity of dataflow derivative, dataflow derivative for short. **C_x**, **C_y** and **C_n** change with **β** and its relationship with **u** and **v** is as follows,

\[
u = V \cos \beta
\]

\[
v = -V \sin \beta
\]

### 3.4. Force Transfer of Ship and Anchor Chain

In order to know the tensile force of anchor chain based on longitudinal mooring force, **Φ_1** (vertical angle of chain’s water point) and **Φ_2** (vertical angle of anchor chain in hawsehole) firstly need to be figured out. According to catenary model and on the premise that the anchor chain does have underwater parts, **Φ_1** can be calculated as.
\[
\phi_t = 180^\circ - 2\arctg(S/d)
\]

S represents for length of underwater anchor chain (m), D for anchorage water depth (m).

Longitudinal tensile force of anchor chain is

\[
T_h = d \cdot \frac{\cos \phi_t}{1 - \cos \phi_t}
\]

\[W\] means anchor chain weight per unit length.

\[\Phi_2\] can be calculated in the following formula,

\[
\Phi_2 = \arccos \frac{1}{d \cdot \left(\frac{w}{T_h'} + \frac{1}{\cos \phi_t}\right)}
\]

The biggest tensile force of anchor chain in hawsehole is:

\[
T_{Max} = T_h / \cos \Phi_2
\]

4. Force Analysis of Buoy Mooring of One-hundred-thousand Ton Non-powered Bulk Cargo Ship

4.1. Mathematical Model Calculating

The state of motion of ship, anchor chain and buoy is ship’s environmental load which results from the synactic action of moment of turning ship of wind force and hydrodynamic force. Under the force action of wind flow and anchor chain of ship bow, vessel is in a stable state for long or short time, because the resultant force from ship’s fore and aft and abeam direction, as well as the sum of all force moment, is zero. Take a one-hundred-thousand tons anti-typhoon buoy for example, making good use of the written calculating software of ship’s environmental load to do mathematical analog analysis and computing, referring to datum of shipform design and historical flow cases ( table 1).

| Wind Direction and Speed (an average of 10 mins) | N | NNE | NE | ENE | E | ESE | SE | SSE |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wind Speed m/s | 43.7 | 33.1 | 33.1 | 37.4 | 27.7 | 28.7 | 34.1 | 34.8 |
| Wind Direction | S | SSW | SW | WSW | W | WNW | NW | NNW |
| Wind Speed m/s | 22.6 | 18.9 | 17.2 | 15.8 | 26.6 | 25.4 | 25.8 | 42.8 |

| Flow Direction and Speed | Rising Tide | Falling Tide |
| --- | --- | --- |
| Flow Direction | 256° | 97° |
| Flow Speed m/s or m/s | 2.48 | 2.16 |

The results under combination of wind and flow superimposed calculated with the following three-group wave force in close direction.

| Wave Design Elements | H1%/m | wave length/m | wave direction/ (°) |
| --- | --- | --- | --- |
| wave height | 2.9 | 2.9 | 2.9 |
| wave length/m | 42.2 | 40.6 | 66.6 |
| wave direction/ (°) | 227 | 237 | 257 |
Result: Firstly, calculating the force of ship and anchor chain under the combination of wind and flow, and then adding selected 15 groups of unfavourable conditions to wave force with close direction to get the final most unfavourable condition. According to the result, three groups of most unfavourable conditions with highest resultant force are given in table 2.

Table 2. Most Unfavorable Working Conditions under the Combination of Wind and Flow

| Steam (°) | Wind (°) | Wind Speed (m/s) | Flow (°) | Wave Speed (m/s) | Wave Height (m) | Wave Height (m) | Resultant Force (KN) | Chain Direction (°) | Chain Force (KN) | Chain Force Instant Wave (KN) | Direction of Resultant Force (°) | Φ₁ (°) | Φ₂ (°) |
|-----------|----------|------------------|---------|------------------|------------------|------------------|----------------------|----------------------|------------------|-----------------------------|---------------------------------|-------|-------|
| 126       | 158      | 34.8             | 256     | 2.5              | 227              | 42.2             | 2.9                  | 4002.5               | 192.2            | 4275.9                      | 4461.7                         | 12.2  | 18.3  |
| 120       | 135      | 34.1             | 256     | 2.5              | 227              | 42.2             | 2.9                  | 3200.1               | 171.4            | 3425.5                      | 3568.5                         | 18    | 20.9  |
| 269       | 338      | 42.8             | 97      | 2.2              | 257              | 66.6             | 4.7                  | 2811                | 291.4            | 3013.0                      | 3282                           | 111.4 | 17.8  |

4.2. Physical Model Test Result
The trial mooring result, based on physical model test, is seen in table 3. Through comparison, things are that mathematical model calculating gets larger results and more conservative and reliable in evaluation.

5. Conclusions
(1) Chain Model Selection. Generally speaking, a ship of ten-hundred-thousand tons is equipped with three-grade stud link chain, 92mm in diameter and AM3 in texture. As stipulated in PRC National Standard Electro-welded Anchor Chains (GB/T549-2008), three-grade stud link chain, 92 in diameter, is designed with 4260kN pulling load and 6080kN breaking load. Therefore, the ten-hundred-thousand buoy is outfitted with underwater anchor chain, 124mm in diameter and AM3 in texture, with 7200KN pulling load and 10280KN breaking load.

Table 3. Physical Model Test Results

| Water level | ballast conditions | parameters of wind, wave and flow | Anchor chain force/kN | ship motion |
|-------------|--------------------|-----------------------------------|-----------------------|-------------|
|             | wind speed/m·s⁻¹ | flow velocity/m·s⁻¹ | significant wave height/m | average | maximum | angle (°) | significant | maximum | angle (°) | significant | maximum | angle (°) |
| high level  | 43.7              | 2.48                  | 3.1                   | 1815      | 4220    | 3.5     | 2.5       | 1.0       | 0.3       | 1.2                 |
| Low level   | 43.7              | 2.16                  | 3.1                   | 1670      | 4120    | 3.5     | 0.25      | 1.0       | 0.3       | 1.2                 |

Note: Test working condition, included angle between wind and flow (30°), wave and flow coming in the same direction.

(2) Single point buoy mooring system adopts boundary condition. Anchor chains, as the boundary condition, are the bottleneck. Wave (wind wave) and current strength (wind drift overlaid) are greatly influenced by wind speed. Considering the predictability of wind speed, when wind speed is over 43.7m/s, buoy cannot moored to vessel.
(3) Length Setting of Anchor Chain of Single Point Mooring System. Through analysis of the relationship between the change of $\Phi_1$ and $\Phi_2$ and chain stress, say chain is too short, its stress will increase several times. For single point mooring ship, the length of chain can be suitably increased, but not be over-increased, because it will affect the navigation safety in whole port, as well as increase chain stress due to increased turning inertia force.

(4) According to force analysis of ships in given conditions and mathematical and physical model test results, about a quarter of ballasts is suitable for various conditions of wind, wave and flow. However, it, in actual use, should be properly adjusted in the light of wind and flow, flow in particular.

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