ON OPERATION CAPABILITIES ANALYSIS OF A 100000 TDW TANKER BY SEAKEEPING CRITERIA

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ABSTRACT

The operation capabilities of a maritime ship have to be assessed during the design, including the seakeeping criteria. In this study a 100000 tdw tanker is considered, with two loading conditions, cargo and ballast. The numerical analyses are developed with own software DYN, module OSC, based on a linear hydrodynamic strip theory. The main oscillation components, heave, pitch and roll, are considered. The analysis includes an extended parametric study for the tanker speed up to 15 knots, different vertical position of the gravity centre, heading angle full range and irregular waves significant height up to 12 m. Also the seakeeping limits have two sets of criteria. The results are pointing out the operation limits of the tanker on combined navigation parameters in irregular waves, by motions and acceleration short term seakeeping criteria.

Keywords: ship oscillations, tanker ship, irregular waves, seakeeping criteria, parametric study.

1. INTRODUCTION

The development of the design concept for a maritime ship involves many criteria to be assessed, according to the design rules of the ship’s classification societies [4],[5],[13].

In this study the seakeeping analysis [1],[2],[10],[11],[14] is selected, for an extended parametric study of the operation capabilities evaluation of a 100000 tdw tanker [8].

The following main parameters are considered: loading case Δ, x_G, cargo (TK1) and ballast (TK2); speed v, 0, 5, 10, 12.5, and 15 kn; the theoretical vertical position of the gravity centre z_G, 8, 9, 10, 11, 12, 13 and 14 m; tanker-wave heading angle μ, 0-360 deg, step 5 deg; irregular waves significant height H_s, 0-12 m, step 0.05 m. Also two sets of limit values for the seakeeping criteria are considered.

The study ship, 100000 tdw tanker [8], has the transversal offset-lines in Fig.1 and the main characteristics in Table 1. Figs.2.a,b and Tables 2.a,b present the transversal stability data and the natural periods for roll oscillations, for the z_G theoretical range.

The seakeeping simulations are done by own program DYN [6], module OSC, for ship’s oscillations in regular and irregular waves, statistical short-term results, based on a linear strip theory hydrodynamic model, in brief presented in section 2. The program DYN-OSC has been previous validated by several experimental tests on scaled models, at towing tank, in regular head, follow and beam wave conditions, with results presented in references [3],[7],[9],[12]. The parametric study aims to test the sensitivity of the operation limits of the 100000 tdw tank, due to the changes of several navigation data.

The dynamic response in regular waves of the 100000 tdw tankers, in terms of response amplitude operators [1],[14] is presented in section 3. The dynamic response in irregular waves and seakeeping criteria assessment [6],[11] are presented in section 4.
The conclusions of this study (section 5) synthesize the 100000 tdw tanker operation limits parametric study by seakeeping criteria.

**Table 1.** The 100000 tdw tanker main data [8]

| $L_{OA}$ [m] | 246 | Case: | TK1cargo | TK2ballast |
|-------------|-----|-------|----------|------------|
| $B$ [m]     | 42  | $\Delta$ [t] | 126457   | 81763      |
| $H$ [m]     | 21.3| $x_c$ [m]  | 126.4    | 128.3      |
| $p$ [t/m$^2$] | 1.025 | $L_{ML}$ [m] | 240      | 232        |
| $g$ [m/s$^2$] | 9.81  | $d_m$ [m]  | 15       | 10         |
| $H_{max}$ [m] | 12  | $T_1$ [s]  | 10.333   | 9.336      |
| stations    | 41  | $T_3$ [s]  | 10.517   | 9.796      |
| points       | 1230| $z_c$ [m]  | 8 – 14   | (step 1)   |
| $\nu_{max}$ [kn] | 15 | $\mu$ [deg] | 0 – 360  | (step 5)   |

**Table 2.a** TK1, stability data and roll periods

| $z_c$ [m] | $GM_{TB}$ [m] | $J_z$ [tm$^2$] | $T_1$ [s] | $\phi_{max}[deg]$ |
|-----------|---------------|---------------|----------|--------------------|
| 8         | 9.562         | 21286956.0    | 9.631    | 49                 |
| 9         | 8.562         | 22003546.10   | 10.334   | 46                 |
| 10        | 7.562         | 22804441.11   | 11.181   | 43                 |
| 11        | 6.562         | 23689642.12   | 12.233   | 39                 |
| 12        | 5.562         | 24659147.13   | 13.547   | 36                 |
| 13        | 4.562         | 25712956.15   | 15.255   | 32                 |
| 14        | 3.562         | 26851071.17   | 17.564   | 28                 |

**Table 2.b** TK2, stability data and roll periods

| $z_c$ [m] | $GM_{TB}$ [m] | $J_z$ [tm$^2$] | $T_1$ [s] | $\phi_{max}[deg]$ |
|-----------|---------------|---------------|----------|--------------------|
| 8         | 11.303        | 13763496.10   | 10.468   | 45                 |
| 9         | 10.303        | 14226821.11   | 11.223   | 43                 |
| 10        | 9.303         | 14744656.12   | 12.074   | 41                 |
| 11        | 8.303         | 15316999.13   | 13.005   | 40                 |
| 12        | 7.303         | 15943851.14   | 14.018   | 39                 |
| 13        | 6.303         | 16625213.15   | 15.265   | 37                 |
| 14        | 5.303         | 17361083.16   | 18.466   | 36                 |

2. THEORETICAL FUNDAMENTS

The seakeeping analysis with own program DYN [6], module OSC, based on a linear strip theory 2D hydrodynamic model [2],[6],[14], has three main steps.

- Dynamic response in regular waves, when the response amplitude operators RAO are obtained by a direct solution in the frequency domain of the motions equations system:

$$\{\{A\}|\{p(t)\}\} + \{B\}|\{\rho(t)\}\} + \{C\}|\{\rho(t)\}\} = \{E_{n1}\}(t)$$

$$\{E_{n1}\}(t) = \{E_{n1}\} \cos \omega t + \{E_{n1}\} \sin \omega t \rightarrow p_{j1}(t) = p_{j1} \cos \omega t + p_{j1} \sin \omega t, \ j = 3,4,5$$

$$p_{j1} = \sqrt{(p_{j1})^2 + (p_{j1})^2} : \omega = \omega_w - \omega \nu \cos \mu / g$$

$$\text{RAO}_j(\omega_w) = p_{j1} \tau (\omega_w) \ j = 3,4,5$$

where: $\{A\}|\{B\}|\{C\}$ are the radiation matrix; $\{E_{n1}\}(t)$ is the regular wave diffraction vector; $\{p(t)\}$ is the dynamic response; $\omega_w$ is the wave encountering frequency; $\omega, \mu$ are the regular wave frequency and heading angle; $\nu$ is the ship speed; $\text{RAO}_j(\omega_w) \ j = 3,4,5$ are the heave, roll and pitch RAO functions.
- Dynamic response in irregular waves, when the most probable short-term statistical motions \( RMS_j (\omega) \) and acceleration \( RMS_{acj} \) (6) amplitudes are obtained:

\[
S_j(\omega_j) = RAO_j^2(\omega_j)S_\omega(\omega_j) \quad j = 3,4,5
\]  

\[
RMS_j = \left( \int S_j(\omega_j)d\omega_j \right)^{0.5} \quad j = 3,4,5
\]  

\[
RMS_{acj} = \left( \int \omega_j^4 S_j(\omega_j)d\omega_j \right)^{0.5} \quad j = 3,4,5
\]

where: \( S_\omega \) is the wave power density spectrum, \( ITTC \) \[10\] (Fig.9); \( S_j \) is the response spectrum.

- The polar diagrams of wave height significant and Beaufort level limits (7) by seakeeping criteria (8) – (11) are obtained, with two sets of admissible values from Table 3:

\[
H_{slim}(\Delta, v, \mu) : B_{lim}(\Delta, v, \mu)
\]  

\[
RMS_z = RMS_x + 0.5 RAO_x + \frac{B}{2} RMS_x + \frac{H_s}{4}
\]

\[
\xi_{aft} = x_F ; \xi_{mid} = 0 ; \xi_{fore} = L - x_F
\]

\[
RMS_{zadm} = H - f_x \xi_{aft, mid, fore} f_x = 0.3m
\]

\[
RMS_z \leq RMS_{zadm}
\]

\[
RMS_{ac3} \leq RMS_{ac3adm} = 0.1g
\]

\[
RMS_{ac4} \leq RMS_{ac4adm} = 6 - 8\ deg
\]

\[
RMS_{ac5} \leq RMS_{ac5adm} = 0.15g/(B/2)
\]

\[
RMS_5 \leq RMS_{5adm} = 3 - 4\ deg
\]

\[
RMS_{ac5} \leq RMS_{ac5adm} = 0.15g/(\min\{\xi_{aft} - \xi_{fore}\})
\]

where: \( x_F \) is the reference still water plane centre longitudinal position (\( x = 0, L \)).

### Table 3 Seakeeping criteria admissible values

| Limits version       | Criteria A | Criteria B |
|----------------------|------------|------------|
| \( RMS_{zadm adm} \) [m] | 7.3        | 7.8        |
| \( RMS_{zmin adm} \) [m]  | 6.0        | 6.5        |
| \( RMS_{zfore adm} \) [m]  | 7.7        | 8.2        |
| \( RMS_{5adm} \) [rad]       | 0.05236    | 0.06981    |
| \( RMS_{5adm} \) [rad]       | 0.10472    | 0.13963    |
| \( RMS_{ac5 adm} \) [m/s^2]  | 0.981      | 0.981      |
| \( RMS_{ac5 adm} \) [rad/s^2] | 0.01224    | 0.01224    |
| \( RMS_{ac5 adm} \) [rad/s^2] | 0.07007    | 0.07007    |

### 3. Dynamic Response in Regular Waves

The dynamic response in regular waves is computed for a wave frequency range of \( \omega = 0-3 \) rad/s, step 0.001 rad/s and wave amplitude \( a_o = 1 \) m, covering the whole oscillations range frequencies of heave, pitch and roll motions. Using equations (1)-(3), the \( RAO \) response amplitude operators are obtained by DYN [6], module OSC, for the parametric study defined in section 1.

### 3.1 Loading case TK1

Figs.3.a-d present a selection of heave \( RAO_3 \) for loading case TK1. The maximum heave results at head-quarter wave, \( \mu = 135 \) deg (Fig.3.a). The influence of ship’s speed for heave response is on \( \omega = 0.5-1.25 \) rad/s at follow wave (Fig.3.b), is negligible at beam wave (Fig.3.c) and is on \( \omega = 0.25-1 \) rad/s at head wave (Fig.3.d).
Figs. 4.a-d present a selection of pitch RAO for loading case TK1. The maximum pitch results at head wave and is very reduced at beam wave (Figs. 4.a,c). The influence of ship’s speed for pitch response is on $\omega=0.25-0.75$ rad/s at follow and head waves (Figs. 4.b,d). RAO

Figs. 5.a-d present a selection of roll RAO for loading case TK1. The maximum roll results at beam wave (Figs. 5.a,b,c), is smaller at quartering wave and zero at follow and head wave. The influence of ship’s speed for roll response is on $\omega=0.25-0.75$ rad/s at aft and fore quarter waves (Figs. 5.b,c), is negligible at beam wave. Due to the significant changes of the natural roll period function to the vertical position of the gravity centre, $\theta=90$ deg TANK1 (100000 tdw); $\theta=8-14$ m (Table 2.a), $T_{\phi}=9.631-17.564$ s ($\omega_0=0.652-0.358$ rad/s), the maximum roll RAO, $\mu=90$ is for $z_G=8$m (Figs. 5.d), due to the fact that the roll hydrodynamic damping decreases when the frequency increase [6],[14].
3.2 Loading case TK2

Figs. 6.a-d present a selection of heave $\text{RAO}_3$ for loading case TK2. The maximum heave results at beam wave (Fig. 6.a). The influence of ship’s speed for heave response is on $\omega = 0.55 - 1.3$ rad/s at follow wave (Fig. 6.b), is negligible at beam wave (Fig. 6.c) and is on $\omega = 0.1 - 1.25$ rad/s at head wave (Fig. 6.d).

Figs. 7.a-d present a selection of pitch $\text{RAO}_5$ for loading case TK2. The maximum pitch results at head wave and is very reduced at beam wave (Figs. 7.a, c). The influence of ship’s speed for pitch response is on $\omega = 0.2 - 1.3$ rad/s at quarter waves (Figs. 7.b, d) and is negligible at beam wave. Analogue to case TK1, the natural roll period changes for $z_G = 8 - 14$ m (Table 2.b), $T_4 = 10.468 - 16.846$ s ($\omega_4 = 0.600 - 0.373$ rad/s), so that the maximum roll $\text{RAO}_4 (\mu = 90)$ is for $z_G = 8$ m (Fig. 8.d), being significant smaller for $z_G = 14$.

Figs. 8.a-d present a selection of pitch $\text{RAO}_3$ for loading case TK2. The maximum roll results at beam wave (Figs. 8.a, b, c), is zero at follow and head wave. In compare to case TK1 (Figs. 5.a, b, c), in this case the roll response has a wider frequency band. The influence of ship’s speed for roll response is on $\omega = 0.25 - 1.25$ rad/s at quarter waves (Figs. 8.b, c) and is negligible at beam wave. Analogue to case TK1, the natural roll period changes for $z_G = 8 - 14$ m (Table 2.b), $T_4 = 10.468 - 16.846$ s ($\omega_4 = 0.600 - 0.373$ rad/s), so that the maximum roll $\text{RAO}_4 (\mu = 90)$ is for $z_G = 8$ m (Fig. 8.d), being significant smaller for $z_G = 14$. 
4. DYNAMIC RESPONSE IN IRREGULAR WAVES

The dynamic response in irregular waves is computed using the RAO functions from section 3 and the ITTC wave power density spectrum from Fig.9 [10], for an unrestricted navigation condition $H_{slimit}$=12m. Using equations (4)-(6), the RMS most probable amplitudes for heave, pitch, roll, motions and accelerations are obtained by DYN [6], module OSC. Based on the seakeeping criteria from equations (8)-(11), the polar diagrams for navigation safety (7) are obtained.

A selection of the statistic short-term results for loading case TK1 (cargo) are included:

- Fig.10.a presents the $H_{slimit}$ for $v$=15kn, $z_g$=8-14m, criteria A (Table 3) and Fig.10.b for $v$=0-15kn, $z_g$=8-14m, at beam sea;
- Figs.11.a,b present the most probable amplitudes for roll, $v$=0 kn, $z_g$=8-14m, at beam sea;
- Figs.12.a,b present the $H_{slimit}$ and $B_{slimit}$ for $v$=0-15kn, $z_g$=12m, criteria A (Table 3);
- Figs.12.c,d present the lower $H_{slimit}$ and heading angle, $v$=0-15kn, $z_g$=8-14m, criteria A;
- Fig.13 presents the $H_{slimit}$ for $v$=0-15kn, $z_g$=12m, criteria B (Table 3);
- Tables 4.a,b present the $H_{slimit}$ and $B_{slimit}$ for $v$=0-15kn, $z_g$=8-14m, criteria A and B.
Fig. 11.a. $RMS_5$ [rad], TK1, $v=0$ kn, $\mu=90\text{deg}$

Fig. 11.b. $RMS\mu_{65}$ [rad/s$^2$], TK1, $v=0$ kn, $\mu=90\text{deg}$

Fig. 12.a. $H_{slimit}\text{[m]}$ (A), TK1, $v=0-15$ kn, $z_G=12$ m

Fig. 12.b. $B_{limit}(A),\text{TK1,}v=0-15$ kn, $z_G=12$ m

Fig. 12.c. $H_{slimit}\text{[m]}$ (A) lower, TK1, $v=0-15$ kn

Fig. 12.d. Lower limit angle (A), TK1, $z_G=8-14$ m

Table 4.a. $H_{slimit}\text{[m]},\, B_{limit}(A),\text{TK1,}d_m=15$ m

| $v$ [kn] | $z_G$ [m] | $H_{slimit}$ [m] | $B_{limit}$ [m] | Criterion |
|----------|-----------|------------------|------------------|-----------|
| 0        | 5         | 5.031-10.452     | 7.61-10.43      | roll.mot. |
| 5        | 5         | 5.126-10.452     | 7.68-10.43      | roll.mot. |
| 8        | 5         | 5.303-10.452     | 7.62-10.43      | roll.mot. |
| 10       | 5         | 5.656-10.452     | 7.77-10.43      | roll.mot. |
| 14       | 5         | 6.456-10.452     | 8.53-10.43      | roll.mot. |
| 6        | 0         | 5.043-10.452     | 7.62-10.43      | roll.mot. |
| 10       | 5         | 5.569-10.452     | 7.98-10.43      | roll.mot. |
| 12       | 5         | 6.197-10.452     | 8.38-10.43      | roll.mot. |
| 14       | 5         | 7.251-10.452     | 9.03-10.43      | roll.mot. |
| 8        | 4         | 4.864-11.387     | 7.50-10.77      | roll.mot. |
| 9        | 4         | 4.961-11.387     | 7.56-10.77      | roll.mot. |
| 10       | 5         | 5.138-11.387     | 7.69-10.77      | roll.mot. |
| 11       | 5         | 5.392-11.387     | 7.86-10.77      | roll.mot. |
| 12       | 5         | 5.909-11.387     | 8.20-10.77      | roll.mot. |
| 13       | 6         | 6.812-11.387     | 8.76-10.77      | roll.mot. |
| 14       | 7         | 7.470-11.387     | 9.26-10.77      | roll.mot. |
| 8        | 12        | 4.823-11.574     | 7.47-10.84      | roll.mot. |
| 9        | 12        | 4.920-11.574     | 7.54-10.84      | roll.mot. |
| 10       | 5         | 5.061-11.574     | 7.63-10.84      | roll.mot. |
| 11       | 5         | 5.285-11.574     | 7.79-10.84      | roll.mot. |
| 12       | 5         | 5.745-11.574     | 8.10-10.84      | roll.mot. |
| 13       | 6         | 6.528-11.574     | 8.59-10.84      | roll.mot. |
| 14       | 7         | 7.637-11.574     | 9.21-10.84      | roll.mot. |
| 8        | 12        | 4.783-11.725     | 7.44-10.90      | roll.mot. |
| 9        | 12        | 4.880-11.725     | 7.51-10.90      | roll.mot. |
| 10       | 9         | 4.985-11.725     | 7.58-10.90      | roll.mot. |
| 11       | 5         | 5.156-11.725     | 7.70-10.90      | roll.mot. |
| 12       | 5         | 5.563-11.725     | 7.97-10.90      | roll.mot. |
| 13       | 6         | 6.219-11.725     | 8.39-10.90      | roll.mot. |
| 14       | 7         | 7.521-11.725     | 9.16-10.90      | roll.mot. |
4.2 Loading case TK2

A selection of the statistic short-term results for loading case TK2 (ballast) are included: - Fig. 14.a presents the $H_{\text{dmax}}$ for $v=15\text{kn}$, $z_G=8-14\text{m}$, criteria A (Table 3) and Fig. 14.b for $v=0-15\text{kn}$, $z_G=8-14\text{m}$, at beam sea; - Figs. 15.a, b present the most probable amplitudes for roll motion and acceleration, $v=0 \text{kn}$, $z_G=8-14\text{m}$, at beam sea; - Figs. 16.a, b present the lower $H_{\text{dmax}}$ for $v=0-15\text{kn}$, $z_G=8-14\text{m}$, criteria A (Table 3); - Fig. 17 presents the $H_{\text{dmax}}$ for $v=0-15\text{kn}$, $z_G=10\text{m}$, criteria B (Table 3); - Tables 5.a, b present the $H_{\text{dmax}}$ and $B_{\text{limit}}$ for $v=0-15\text{kn}$, $z_G=8-14\text{m}$, criteria A and B.

![Diagram](image1)

**Fig.13.** $H_{\text{dmax}}[\text{m}](B), v=0-15\text{kn}, z_G=12\text{m}

**Table 4.b.** $H_{\text{dmax}}[\text{m}], B_{\text{limit}}(B), TK1, d_r=15\text{m}

| $v[\text{kn}]$ | $z_G[\text{m}]$ | $H_{\text{dmax}}[\text{m}]$ | $B_{\text{limit}}$ | Criterion |
|---------------|-----------------|----------------------|-------------------|-----------|
| 0             | 8               | 7.666-11.045         | 9.23-10.65        | heave mot.|
| 15            | 8               | 7.340-12.000         | 9.07-11.00        | heave mot.|
|               | 9               | 7.496-11.045         | 9.15-10.65        | heave mot.|
|               | 10              | 7.375-11.045         | 9.09-10.65        | heave mot.|
|               | 11              | 7.325-11.045         | 9.06-10.65        | heave mot.|
|               | 12              | 7.458-11.045         | 9.13-10.65        | heave mot.|
|               | 13              | 7.790-11.045         | 9.29-10.65        | heave mot.|
|               | 14              | 8.467-11.045         | 9.61-10.65        | heave mot.|
|               | 8               | 7.469-12.000         | 9.13-11.00        | roll.mot. |
|               | 9               | 7.340-12.000         | 9.07-11.00        | heave mot.|
|               | 10              | 6.943-12.000         | 8.85-11.00        | roll.mot. |
|               | 11              | 6.716-12.000         | 8.70-11.00        | roll.mot. |
|               | 12              | 6.948-12.000         | 8.85-11.00        | roll.mot. |
|               | 13              | 7.349-12.000         | 9.08-11.00        | heave mot.|
|               | 14              | 7.921-12.000         | 9.35-11.00        | heave mot.|

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Table 5.1. $H_{\text{lim}}[\text{m}], B_{\text{null}} (\text{A}), \text{TK2}, z_2=10 \text{m}$

| $v$ [kn] | $z_2$ [m] | $H_{\text{lim}}$ [m] | $B_{\text{null}}$ | Criterion |
|----------|-----------|----------------------|------------------|-----------|
| 0        |           |                      |                  |           |
| 8        | 8.787-10.259 | 9.81-10.36 | heave mot.        |           |
| 10       | 8.842-10.259 | 9.79-10.36 | heave mot.        |           |
| 11       | 8.888-10.259 | 9.81-10.36 | heave mot.        |           |
| 12       | 8.877-10.361 | 9.85-10.40 | heave mot.        |           |
| 14       | 9.111-10.601 | 9.92-10.48 | heave mot.        |           |
| 8        | 8.709-10.654 | 9.73-10.50 | heave mot.        |           |
| 9        | 8.695-10.654 | 9.72-10.50 | heave mot.        |           |
| 10       | 8.709-10.654 | 9.73-10.50 | heave mot.        |           |
| 11       | 8.755-10.654 | 9.75-10.50 | heave mot.        |           |
| 12       | 8.816-10.654 | 9.78-10.50 | heave mot.        |           |
| 13       | 8.907-10.654 | 9.82-10.50 | heave mot.        |           |
| 14       | 9.038-10.654 | 9.88-10.50 | heave mot.        |           |

Table 5.2. $H_{\text{lim}}[\text{m}], B_{\text{null}} (\text{B}), \text{TK2}, z_2=10 \text{m}$

| $v$ [kn] | $z_2$ [m] | $H_{\text{lim}}$ [m] | $B_{\text{null}}$ | Criterion |
|----------|-----------|----------------------|------------------|-----------|
| 0        |           |                      |                  |           |
| 8        | 9.512-10.848 | 10.08-10.58 | heave mot.        |           |
| 9        | 9.463-10.848 | 10.07-10.58 | heave mot.        |           |
| 10       | 9.439-10.848 | 10.06-10.58 | heave mot.        |           |
| 11       | 9.447-10.848 | 10.06-10.58 | heave mot.        |           |
| 12       | 9.486-10.961 | 10.07-10.62 | heave mot.        |           |
| 13       | 9.567-11.137 | 10.10-10.68 | heave mot.        |           |
| 14       | 9.698-11.397 | 10.15-10.78 | heave mot.        |           |
| 8        | 9.083-11.917 | 9.93-10.97 | heave mot.        |           |
| 9        | 9.101-11.917 | 9.91-10.97 | heave mot.        |           |
| 10       | 9.146-11.917 | 9.93-10.97 | heave mot.        |           |
| 11       | 9.215-11.917 | 9.97-10.97 | heave mot.        |           |
| 12       | 9.291-11.917 | 10.00-10.97 | heave mot.        |           |
| 13       | 9.385-11.917 | 10.04-10.97 | heave mot.        |           |
| 14       | 9.496-11.917 | 10.08-10.97 | heave mot.        |           |
5. CONCLUSIONS

For a 100000 dwt tanker [8] (Fig.1, Tables 1, 2), based on own code DYN [6], with theoretical model (1)-(6), a parametric study has been developed ($\Delta$, $z_{\text{slimit}}$, $v$, $\mu$, $H_\theta$) for the dynamic response in regular and irregular waves, resulting the operation capabilities limits (7), by seakeeping criteria (8)-(11) (Table 3).

From the regular wave’s dynamic response, 2590 cases, the response amplitudes operators are obtained (Figs.3-8). The heave $\text{RAO}_{\text{H}}$ is maxim at quarter-head wave for TK1 and at beam wave for TK2. The pitch $\text{RAO}_{\text{P}}$ is maxim at head waves for both loading cases and much reduced at beam waves. The roll $\text{RAO}_{\text{R}}$ is maxim at beam waves, with zero values at follow and head waves.

For reference $v=0$ kn, $\mu=90$ deg. (Figs. 5.d, 8.d.), the maximum roll $\text{RAO}_{\text{R}}$ is for $z_\theta=8m$ and decreases for $z_\theta=9-14m$, due to the increase of the hydrodynamic damping while the natural period increase (Tables 2,a,b). The ship’s speed influence is reduced at beam waves, being significant on the other heading angles.

From the irregular wave’s dynamic response, 621600 cases, the short-term most probable amplitudes $RMS$ and the operation limits in terms of polar diagrams $H_{\text{limit}}$, $B_{\text{limit}}$ are obtained (Figs.10-17, Tables 4,5). The main restriction criteria are heave (9) and roll (10) motions for TK1 and only heave motion for TK2. The influence of the $z_\theta=8-14m$ over the roll $RMS_\theta$, $RMS_{\text{side}}$ is very significant (Figs.11,15), affecting also the vertical $RMS_H$ (8). The $z_\theta$ influence on operation limits is mainly on beam and quarter sea (Figs.10,14).

The operation limits for criteria A are in the range: $H_{\text{limit}}=4.783-11.725m$ ($B_{\text{limit}}=7.44-10.90$) for TK1, $H_{\text{limit}}=8.537-11.280m$ ($B_{\text{limit}}=9.64-10.73$) for TK2. If the reduced criteria B (Table 3) are considered, the operation limits are improving: $H_{\text{limit}}=7.469-12m$ ($B_{\text{limit}}=9.13-11$) for TK1, $H_{\text{limit}}=9.083-11.917m$ ($B_{\text{limit}}=9.90-10.97$) for TK2. A significant influence of the ship’s speed and gravity centre position is recorded (Figs.12,13,16,17, Tables 4,5).

Further studies will extend this analysis on other ship types and loading conditions.

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