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# SHIP DRIFT ANGLE ANALYSIS IN UNSHELTERED CHANNEL NAVIGATION AND APPLICATION OF ESCORT TUGS

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***Abstract.*** *Over the years, the naval industry has been the most used method to transport goods and materials around the globe. The large capability of carrying cargo as well as its low cost when compared to other transport methods are some of the reasons that makes the naval industry to be the most competitive one. Due to its importance for the global economy, constant research has been developed in order to, each time more, increase the vessels size and consequently augment their load capacity.*
*Since it is one of the most relevant safety criteria of operation, maneuverability performance became an important factor in the design and development process of the increasingly larger vessels. Such performance depends on several factors, such as the vessel's drift angle and its rudder angle. This paper seeks to determine those angles in a steady state scenario through computational procedures in order to analyze their behavior when subjected to known environmental conditions. Moreover, it seeks to inspect the effect on both angles caused by the addition of an escort tug.*

***Keywords:*** *ship drift angle, rudder angle, steady state, environmental forces, escort tugs*

## 1. INTRODUCTION

Nowadays, the naval industry represents the largest share of world trade due to its capability to transport massive quantities of goods within long distances requiring less resources than other transportation methods. In this sense, due to the necessity of constant expansion and improvement of the carrying capacity of the vessels to meet the global demand, both the dimension of ships and the traffic at the sea are expected to increase (Kelman, 2008; Simonsen, 2000). Besides, to guide a ship is an activity that requires specific skills since hydrodynamic forces and moments, with non-linear behaviors, can sudden change their actuation on the vessel, depending on various situations of navigation (Ikeda *et al.*, 2011).

Considering this scenario, maneuverability is one of the most critical issues regarding not only performance of ships in seaways but also maritime safety and marine environmental protection (Paroka *et al.*, 2016). Such importance can be justified by the potential that better maneuverability characteristics have to avoid some common accidents in ship operation, such as collision and grounding (Perez and Clemente, 2017). For this reason, the International Maritime Organization (IMO) has adopted a standard procedure to evaluate ship maneuverability (IMO, 2002).

Several parameters are necessary to evaluate ship maneuverability performance, and, for instance, a vessel's drift angle as well as its rudder angle are relevant in such analysis (Simonsen, 2000), being the focus of this paper.

Effects of drift angles are important for all types of structures and vehicles, including those performing in land, sea, air, and space. Force and moment data for several drift angles play a key role on their design ((Longo and Stern, 2002). Particularly on sea, when a ship moves with a drift angle, it becomes a lifting surface, which generates a force pushing the ship sideways, or in a direction normal to the travelling direction (Kramer *et al.*, 2016). In this sense, the steady state equilibrium on course direction can be achieved by combining the hydrodynamic induced effect with the environmental conditions and the rudder efforts (Paroka *et al.*, 2015).

However, when navigating in narrow channels, only the rudder actuation may not be enough to ensure safety during a maneuver. Therefore, other limitations are necessary to be imposed. As an example of such limitation one can cite the usage of escort tugs (SEP/PR *et al.*, 2016).

Due to the accidents occurred in the past, the requirements concerning tanker structures have been tightened. In response to that, one of the measures taken was the development of the escort tugs, which were designed to assist a vessel at high speeds, being able to steer and arrest it. In addition, the escort tugs were designed with the objective to bring a disabled tanker rapidly and safely under control in the event of a machinery system failure while imposing the minimum possible effect on the tanker's normal operations (Balakrishnan and Sasi, 2016).

Escort tugs are used especially in case of large vessels with hazardous cargoes docking in harbors whose access is made difficult by climatic or geographical factors. In that way, some basic principles are necessary, such as tugs working at the stern of a vessel on tow at cruising speed, a high bollard pull, and others (Couce *et al.*, 2015). In the Brazilian context, escort tugs are starting to operate to improve the safety in unsheltered channel navigation (Feitoza, 2016).

## 2. METHODOLOGY

In order to evaluate the drift angle and rudder angle in steady state condition, a mathematical formulation was developed. This formulation combined the hydrodynamic effects resulting of the drift angle for a known environmental condition of wind, current, wave, as well as rudder efforts to generate a system of two equilibrium equations which demanded computational methods for a solution to be achieved. In addition, for this formulation, it was considered the influence of a force applied by an escort tug at the stern of the ship.

### 2.1 Mathematical Procedure

The representation of the efforts in question, and the illustration of their angles (measured in clockwise direction) can be observed in Fig. 1. To obtain a steady motion in the direction of the course, indicated by x, the equilibrium equations were obtained in relation to the y-axis (perpendicular direction to the ship course) and z-axis (perpendicular direction of ship plane), resulting in a non-linear system determined by $\psi$ and $\psi_R$.

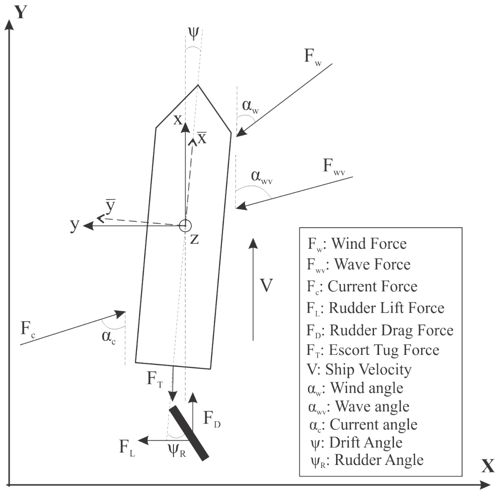

Figure 1. Representation of Efforts and Angles

The non-linear system resulting from the equilibrium equations can be summarized in:

$$\begin{cases} \sum F_y(\psi, \psi_R) = 0 & (1) \\ \sum M(\psi, \psi_R) = 0 & (2) \end{cases}$$

The contribution of each term of the formulation is described below:

#### 2.1.1 Wind Effect

Wind forces can be estimated by considering geometric factors of the vessel as well as coefficients obtained by model tests. The following expressions for the resultant efforts on $\overline{x}$, $\overline{y}$ and z directions are reached (OCIMF, 1977):

$$\begin{cases} F_{\overline{x}}^w = \frac{1}{2}\rho_{air} A_F V_w^2 C_x(\alpha_w) & (3) \\ F_{\overline{y}}^w = \frac{1}{2}\rho_{air} A_L V_w^2 C_y(\alpha_w) & (4) \\ M^w = \frac{1}{2}\rho_{air} A_L L V_w^2 C_z(\alpha_w) & (5) \end{cases}$$

Where $\rho_{air}$ is the air density; the geometric factors $A_F$, $A_L$ and $L$ are, respectively, the emerged frontal and lateral areas and the length of the vessel; $V_w$ is the relative speed between the wind and the vessel; $C_x$, $C_y$ and $C_z$ are the experimental dimensionless wind coefficients; $\alpha_w$ is the angle of incidence relative to axis $o\overline{x}$.

### 2.1.2 Current and Hydrodynamic Effect

To evaluate the current efforts on a vessel navigating with advanced speed ($V \neq 0$), being affected by a current velocity $V_c$ and incidence angle with respect to $o\overline{x}$ denoted by $\alpha_c$, it is required to deal with the hydrodynamic induced effect by defining the relative speed $V_{vc}$ and the relative direction $\beta_c$, between vessel's movement and the current direction. Considering that, the efforts are given by (OCIMF, 1977):

$$\begin{cases} F_{\overline{x}}^c = \dfrac{1}{2}\rho_{water} T L V_{vc}^2 C_x(\beta_c) & (6) \\ F_{\overline{y}}^c = \dfrac{1}{2}\rho_{water} T L V_{vc}^2 C_y(\beta_c) & (7) \\ M^c = \dfrac{1}{2}\rho_{water} T L^2 V_c^2 C_z(\beta_c) & (8) \end{cases}$$

Where $\rho_{water}$ is the density of water; $T$ is the vessel's draft; $C_x$, $C_y$ and $C_z$ are the experimental current coefficients.

### 2.1.3 Wave Effect

Different approaches can be adopted to describe a wave on its spectral distribution of energy, considering both short and long crested waves. To define either regular waves or non-fully developed seas the JONSWAP spectrum, Fig. 2, can be used (Tannuri *et al.*, 2014).

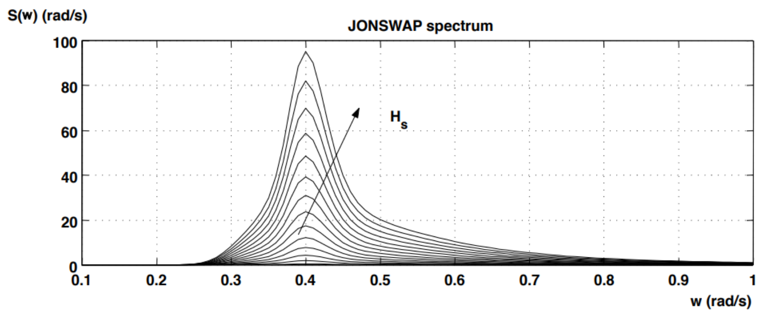


Figure 2. JONSWAP Spectrum (Fossen, 2011)

The wave spectrum can be written as a function of the frequency $\omega$:

$$S(\omega) = \frac{\alpha_o g^2}{\omega^5} \exp\left(-\frac{5}{4}\left(\frac{\omega_o}{\omega}\right)^4\right) \gamma^{\exp[-(\omega-\omega_o)^2/(2\sigma^2\omega_o^2)]} \tag{9}$$

With:

$$\begin{cases} \omega_o = \dfrac{2\pi}{T_p} & (10) \\ \gamma = 6.4 T_p^{-0.491} & (11) \\ \alpha_o = \dfrac{5 H_s^2 \omega_o^4}{16 g^2}(1 - 0.287\log(\gamma)) & (12) \\ \sigma = \begin{cases} 0.07, & \text{if} \quad \omega \leq \omega_o \\ 0.09, & \text{if} \quad \omega > \omega_o \end{cases} & (13) \end{cases}$$

Where $T_p$ is the peak period; $H_s$ the wave height.

Considering a random unidirectional sea with spectrum $S(\omega)$ and incidence direction $\alpha_{wv}$, the slow drift forces and moments in surge, sway and yaw direction can be estimated by the integral along the frequency of the drift coefficient times the spectrum, given by the following relationships (Tannuri, 2002):

$$\begin{cases} F_{\overline{x}}^{wv} = \int_0^{\infty} 2D_x(\omega, \alpha_{wv})S(\omega)d\omega \approx \int_0^{\Omega} 2D_x(\omega, \alpha_{wv})S(\omega)d\omega & (14) \\ F_{\overline{y}}^{wv} = \int_0^{\infty} 2D_y(\omega, \alpha_{wv})S(\omega)d\omega \approx \int_0^{\Omega} 2D_y(\omega, \alpha_{wv})S(\omega)d\omega & (15) \\ M^{wv} = \int_0^{\infty} 2N_z(\omega, \alpha_{wv})S(\omega)d\omega \approx \int_0^{\Omega} 2N_z(\omega, \alpha_{wv})S(\omega)d\omega & (16) \end{cases}$$

Where $D_x$, $D_y$ and $D_z$ are the drift coefficients for surge, sway and yaw, respectively.

To perform the numerical approximation of the integral it was used the same range of frequencies in which the coefficients are delimited.

#### 2.1.4 Rudder Effect

Rudders can be defined as a foil designed to produce a lifting force acting across the direction of the incoming flow to control horizontal motion of all types of marine vehicle. The lifting action of the foil arises from the difference in the average pressure of the fluid over the upper and lower surfaces of the lifting foil (Molland and Turnock, 2007).

The total force can be resolved into a lift, perpendicular, and a drag, parallel, component to the fluid stream, given in terms of the rudder area $A_r$, the relative velocity of the fluid $V_r$ and the dimensionless coefficients evaluated on the effective rudder angle $\alpha = \psi + \psi_R$ by the expressions (Molland and Turnock, 2007):

$$\begin{cases} F_l^r = \frac{1}{2}\rho_{water} A_R V_r^2 C_l(\alpha) & (17) \\ F_d^r = \frac{1}{2}\rho_{water} A_R V_r^2 C_d(\alpha) & (18) \end{cases}$$

The increment of speed flow downstream the propeller can be approximated by using axial momentum theory (considering the propeller capable of imparting axial motion to a fluid), resulting in the equation (Molland and Turnock, 2007):

$$V_{xr} = V_i + \left(0.5 + \frac{0.5}{1 + 0.15(X/D_p)}\right)\left(\sqrt{V_i^2 + \frac{8T_{prop}}{\rho_{water}\pi D_p}} - \text{sign}(V_i)V_i\right) \quad (19)$$

Where $X$ and $D_p$ are geometrical factor representing, respectively, the distance between the main propeller and the rudder axis and the main propeller diameter; $V_i$ is the inlet speed water in the propeller and $T_{prop}$ is the propeller thrust.

#### 2.1.5 Tug Effect

To analyze the tug influence on the maneuverability of the vessel, represented by the angles $\psi$ and $\psi_R$, it was considered that the tug force was always parallel to the course direction, as shown in Fig. 1, representing an increase at the propeller thrust ($T_{prop}$), represented by the Eq. (20), and also a contribution on z-axis equilibrium equation due to the drift movement of the vessel.

$$T_{prop} = \overline{T}_{prop} + F_T \quad (20)$$

Where $\overline{T}_{prop}$ is the propeller thrust without the actuation of the escort tug.

### 2.2 Computational Procedure

In order to easily input the environmental parameters as well as the information regarding the navigation of the towed vessel and the actuation of the escort tug, a user-friendly interface was developed. By using this interface, the user could independently modify each individual parameter, in order to understand the specific influence of each one of them. The development of such tool was of extreme importance on the analysis process, allowing the user to graphically view the obtained results.

An adaptation of this interface (the original was developed in Portuguese) can be observed in Fig. 3 and Fig. 4, bellow:

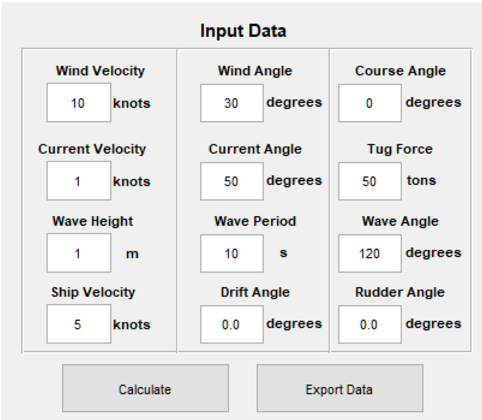


Figure 3. Control Panel

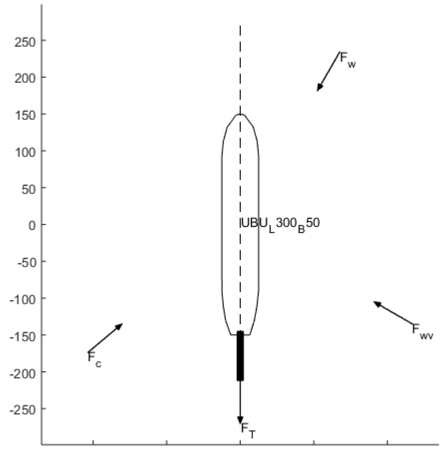


Figure 4. Results Preview

With the input data and the values for the experimental coefficients, it is possible to determine the numerical value of each force or momentum component involved on the steady state analysis.

Therefore, to solve the non-linear system defined by Eq. (1) and Eq. (2) a MatLab® routine based on Newton-Raphson Method was elaborated, in which drift and rudder angles ($\psi$ and $\psi_R$) are determined iteratively for the corresponding equilibrium condition. Looking to ensure the convergence of the method, a range of initial values was considered.

## 3. RESULTS AND DISCUSSION

In order to validate the developed algorithm and to observe the influence of the use of the escort tug, simulations were performed in the Maritime and Waterways Simulator (SMH). Data from the internal documentation of the Numerical Offshore Tank (TPN-USP) (Tannuri *et al.*, 2014) was used in order to obtain the vessel characteristics and environmental coefficients.

In the presented case, it was considered the following information about the ship: Capesize Bulk Ship, Length of 300m, Draft of 18.8m. The data from the environmental condition can be observed on the table presented in Fig. 5, which also shows the results generated by the MatLab® routine for one of the cases tested (Half Ahead, $V = 7.5$ knots, No Tug).

| | | |
|---|---|---|
| Ship | UBU_L300_B50 | |
| Wind Velocity | 20 | knots |
| Wind Angle | 45 | graus |
| Current Velocity | 1.4 | knots |
| Current Angle | 210 | degrees |
| Wave Height | 0 | m |
| Wave Period | 10 | s |
| Wave Angle | 0 | degrees |
| Ship Velocity | 7.5 | knots |
| Course Angle | 90 | degrees |
| Drift Angle | -8.6 | degrees |
| Rudder Angle | 0.5 | degrees |
| Tug Force | 0 | tons |

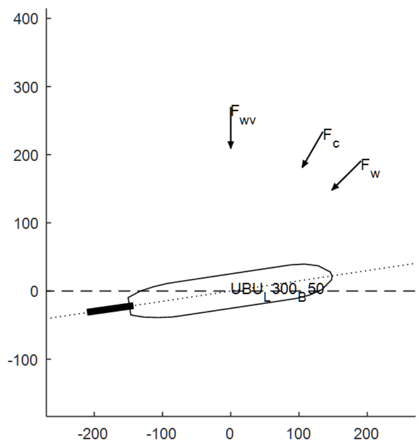


Figure 5. Results of the MatLab® Routine

To validate the results, it was also run a time-domain simulation (using SMH), providing the variation of drift and rudder angle over time, which can be observed, respectively, on Fig. 6 and Fig. 7.

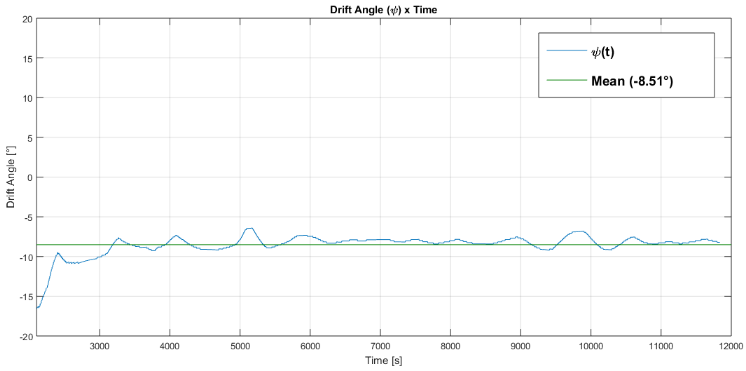


Figure 6. Drift Angle $\psi$ on Simulator

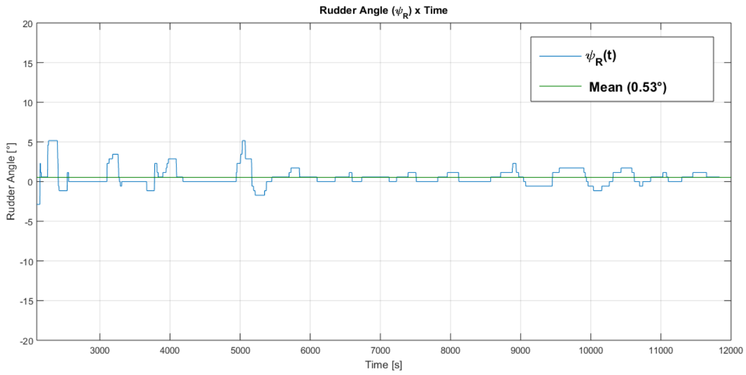


Figure 7. Rudder Angle $\psi_R$ on Simulator

As consequence of the difficulty in obtaining a constant value for the drift and rudder angles over time, the mean values ($\overline{\psi} = -8.51^o$ and $\overline{\psi_R} = 0.53^o$) were used for comparison criteria.

In that sense, it may be noticed quite adherence between the outcomes of both methods, the computational routine and the time-domain simulation. However, with those preliminary results it is not possible to evaluate the influence of the escort tug. To deal with this issue, 2 more tests were performed considering different commands, involving changing of speed and actuation of the tug for the same external condition. The results of the 3 tests accomplished are shown on Tab. 1 bellow:

Table 1. Comparison of Results (Program and Simulator)

| | Command | Average Speed | Tug Force | $\psi$ (program) | $\psi$ (simulator) | $\psi_R$ (program) | $\psi_R$ (simulator) |
|---|---|---|---|---|---|---|---|
| Case 1 | Half Ahead | 7.5 knots | 0 tons | -8.6$^o$ | -8.5$^o$ | 0.5$^o$ | 0.5$^o$ |
| Case 2 | Half Ahead | 5.5 knots | 40 tons | -11.4$^o$ | -11.1$^o$ | -0.6$^o$ | -0.7$^o$ |
| Case 3 | Slow Ahead | 4.5 knots | 0 tons | -13.4$^o$ | -13.1$^o$ | 1.4$^o$ | 1.3$^o$ |

From the collected data, it can be observed that the tug acts in first place to reduce the vessel's speed. By comparing cases 1 and 2 one can note that, although both scenarios were simulated with the same power command (half ahead), they presented different average speeds. Moreover, it may be notice that the drift angle ($\psi$) suffers more influence from the vessel's advance speed and the environmental condition than from tug's force of actuation. Since the environmental conditions remained fixed, the obtained drift angle variation had a direct relation with the average speed change. By observing the cases from 1 to 3, one can realize that the vessel's average speed reduction is directly responsible for the absolute value increase of the drift angle.

On the other hand, the same phenomenon did not occur if we analyze the rudder angle ($\psi_R$). Despite of the decrease on the vessel's average speed from case 1 to 2, the absolute value of the rudder angle remained almost unchanged, implying that, even with smaller advance speeds, the rudder can adequately control the vessel. This result evidence the influence of the escort tug, allowing a higher maneuverability in lower speeds.

Finally, analyzing the rudder angle relationship between cases 1 and 3, with no tug influence, it is possible to note that, with the decrease of the vessel's speed, larger rudder angles are necessary to keep it under control. Therefore, worse maneuverability characteristics are experienced for vessels navigating with low advance speeds.

## 4. CONCLUSION

This paper presented a mathematical formulation and a computational method to determine some ship maneuverability conditions in a steady state known environment condition, without the necessity of running time-domain simulation, which demands time and personnel. It also presented tests and discussions considering the influence of escort tugs, whose relevance increase in large vessels navigation.

After performing the simulations, it was possible to analyze the behavior of the drift and rudder angles for a specific input condition. For the first study, it was shown a direct dependency between the vessel's speed and the drift angle ($\psi$), regardless the efforts of the tugboat. For the second study, overlooking the tug effort, a similar relationship can be observed. Therefore, any decrease on the vessel's advance speed implies on an increase of its rudder angle ($\psi_R$). However, considering the escort tug actuation, its influence on the towed vessel to decrease its velocity does not cause significantly rudder angle changes. Therefore, the actuation of escort tugs helps to increase the safety and keep desired maneuverability characteristics.

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