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Early-design issues of a gas propelled escort tug

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Abstract. Tethered escort of ships is performed by specially designed tugs linked by a tow-line to a strong point aft of the assisted ship. In fact, the tug is called to control the course and speed of the assisted ship in an emergency situation), so reducing the risk of grounding or collision. A substantial number of studies about ship casualties shows the grounding as the predominant accident when the ship is approaching the harbour or narrow fairways. In order to take part in escort operations, a tug must be provided with the additional service notation *escort tug*, which confirms its specific capabilities in accordance with particular stability criteria that will be harmonised by International Maritime Organisation from 2020. In case the tug should be propelled with Liquefied Natural Gas, then dedicated issues related to containment system should be solved. Through this paper, an overview will be given upon the possible escort operations that an escort tug could face during his operational life, together with the possible types/configurations of tugs that can be used for this kind of operations. Moreover an example will be given on the determination of escort performances by means of a self developed code on a sample tug.

Keywords. Escort tug, Steering force, Braking force, Dynamic equilibrium, LNG propulsion

1. Introduction

An escort tug is not performing the same kind of duty requested to traditional harbour tugs [1]. In fact, according to the ship velocity, two possible towing modes can be performed by a tug: direct and indirect [2]. The direct towing mode is performed at low speed (generally lower than 5 knots) and involves vessels that have a relatively small size with good manoeuvring attitude. Those tugs should be capable to deliver push and pull forces all around 360 degrees by aligning propeller thrust with the tow-line. In this case, the main performance parameter of the vessel is given by the total installed power on board. In indirect mode, the vessel speed is higher (6 to 10 knots) and a conventional tug cannot be used, but a vessel with escort notation, means an escort tug, is required [3,4]. The indirect towing operations imply the necessity to use the hydrodynamic characteristics of the vessel hull to generate the sufficient lift/drag forces orienting the tug with an appropriate drift angle. When the tug is not delivering any force to the ship and the speed

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of the connected vessels is less than 6 knots, the operation is properly defined as a ship-assist mode. To be correctly considered escort capable, a tug must safely and effectively provide steering and/or braking forces to a connected ship at speeds higher than 6 knots. This typically occurs using a combination of hydrodynamic lift and drag generated by hull and skeg [9], tow-line tension, and thrust given by the main propulsors.

Due to this particular working duties, the tug is operating at relatively high heeling angles such that the stability requirement fulfilling are mandatory. In this sense, the determination of hydrodynamic forces acting on the hull [5] is extremely important to evaluate the final equilibrium of the vessel, together with the evaluation of the thrust delivered by propulsors [6] and the aim to minimise the absorbed power [7]. In case the vessel should be propelled with Liquefied Natural Gas (LNG), than also the issue of the internal arrangement [8]and of the gas containment system became relevant. In the present work, the main issues related to the early-design of a gas fuelled vessel will be described, starting from the different tug configurations and different gas containment system up to the stability issue and force equilibrium. Moreover, an example will be given on how to enhance the escort performance determination, giving to the tug master indications on the safety of the escort operation.

2. Type of escort tugs

Efficient escort performances can be attained through tugs having excellent manoeuvre capability, high propulsive thrust, and large steering and braking forces produced aft of the assisted ship, as well. In general, tugs fitted with propulsion and steering drives able to provide maximum thrust around 360° are used. They may be equipped with Voith-Schneider vertical axis rotors (VSP) or with azimuthal rudder ducted propellers having either fixed pitch (FP) or controllable pitch (CP). Of course, the adoption of one of the above mentioned propulsive system requires the modification of the main hull form parameters and appendages configuration, resulting in a totally different kind of escort tug. In any case, there are just a few examples in the literature on general guidelines for a tug design [10,11], mainly given by dedicated design companies. For such a reason it is necessary to distinguish between the main typologies of escort tug that can be found in the worldwide tug fleet.

2.1. Stern drive tugs

This category of tug is probably the most commonly adopted in the world. The propulsive configuration of the vessel is composed of two azimuth thrusters located at the vessel stern. This kind of configuration is giving the possibility to have a sufficiently high maneuvrability of the unit while keeping a high value of the bollard pull achievable with the vessel. ASD tugs are not used only for escort operation, but also in standard towing operations. Once also escort activities have to be performed with an ASD tug, it is advisable to increase the skeg dimensions. In fact, by increasing the lateral projected area of the hull and by lengthening the skeg to the bow it is possible to increase the hydrodynamic forces generated by the hull. In Figure 1 a comparison is given between these two possibilities, showing the different skeg configurations between the two options.

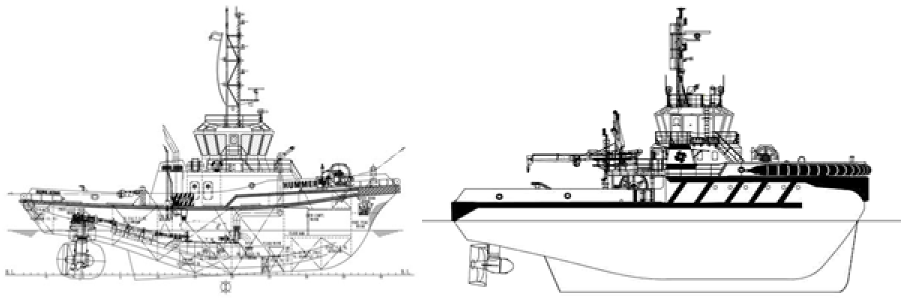

Figure 1. Stern drive tugs (ASD) for standard towing operations (*left*) and for escort operations (*right*)

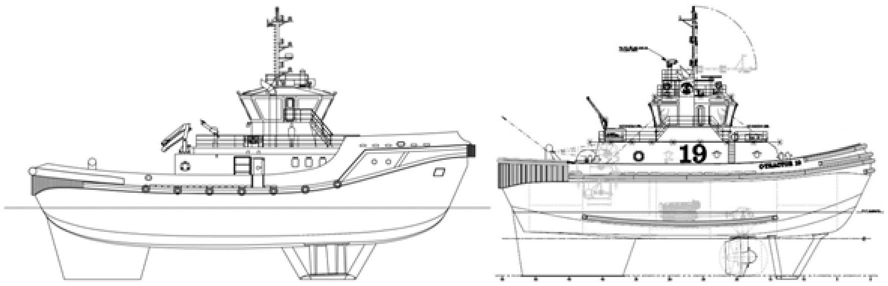

Figure 2. Tractor tug equipped with VSP propulsors (*left*) and with conventional azimuth drives (*right*)

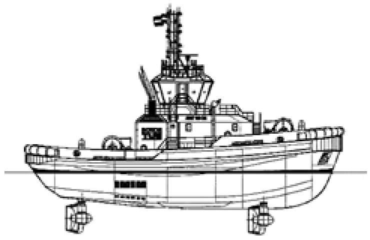

Figure 3. Rotor tug example

2.2. Tractor tugs

The tractor tug (or originally water tractor) is a unique tug concept developed by Voith-Schneider for the use of cycloidal propellers as a propulsive device [12]. Besides the development of VSP propelled tugs, other units were also developed, considering standard thrusters for steering and propulsion. In both cases, the propulsion/steering system is located in one of the end of the vessel (generally to the bow) and is composed by two devices installed at the same longitudinal position, so being shifted only in the lateral direction. To protect the propulsion device from possible damages due to groundings or contacts with external agents, special protections are installed around (in case of VSP) or in front of the propulsive device. On this point of view, this hull shape grants higher maneuvring characteristics with respect to a conventional ASD tug. To balance the steering and braking force it is necessary to fit an additional fin on the opposite end of the vessel with respect to propulsors' position. In Figure 2 the two most commonly used configurations for a tractor tug are represented, highlighting the typical fin located at the stern of the vessel.

2.3. Rotor® tugs

This particular kind of escort tug is a patented concept in the tug design with a unique propulsion system utilising three main engines, each driving a fully azimuth propulsion unit. Two propulsion units are located forward off the centreline, in the normal tractor configuration, with the third unit aft off the centreline replacing traditional aft skeg. The lack of a substantial skeg reduces resistance to turning and cuts down the influence of a ship propeller wash when working in close proximity to large vessels underway. In Figure 3 an example is given of a rotor tug, highlighting the absence of the fin in the aft-ship, with the presence of the two thruster groups.

3. Liquefied gas containment system

A liquefied gas containment system is an overall arrangement for containing cargo and/or combustible including: a primary barrier (the combustible tank), a secondary barrier, an associated thermal isolation, any intervening spaces and adjacent structures to support these elements. Moreover the design life of the containment system should be no less than the maximum between ship operational life and 20 years, granting that a leak from the tank or its connections does not endanger the ship, persons or the environment.

The containment systems are to be provided with a complete secondary liquid-tight barrier capable of safely containing all potential leakages through the primary barrier and, in conjunction with the thermal insulation system, of preventing lowering of the temperature of the ship structure to an unsafe level.Liquefied gas fuel containment system for which the probability for structural failures to develop into a critical state has been determined to be extremely low but where the possibility of leakages through the primary barrier cannot be excluded, shall be equipped with a partial secondary barrier and small leak protection system capable of safely handling and disposing of the leakages. The secondary barriers in relation to the tank types must be provided in accordance with the IGF Code [13]. As defined in the IGF Code and depending mainly on the design pressure, there are three different types of independent tanks: these are known as *Type A*, *Type B* and *Type C*.

Type A tanks are constructed primarily of flat surfaces. The maximum allowable tank design pressure in the vapour space for this type of system is 0.70 barg; this means cargoes must be carried in a fully refrigerated condition at or near atmospheric pressure (normally below 0.25 barg). *Type B* tanks can be constructed of flat surfaces or they may be of the spherical type. *Type B* tank requires only a partial secondary barrier in the form of a drip tray. A protective steel dome covers the primary barrier above deck level and insulation is applied to the outside of the tank. *Type C* tanks are normally spherical or cylindrical having design pressures higher than 2 barg. The tank may be vertically or horizontally mounted. For these tanks the design stresses are kept low. Accordingly, no secondary barrier is required for *Type C* tanks and the hold space can be filled with either inert gas or dry air. With *Type C* tanks there is comparatively poor utilization of the hull volume; however, this can be improved by using bi-lobe type tanks.

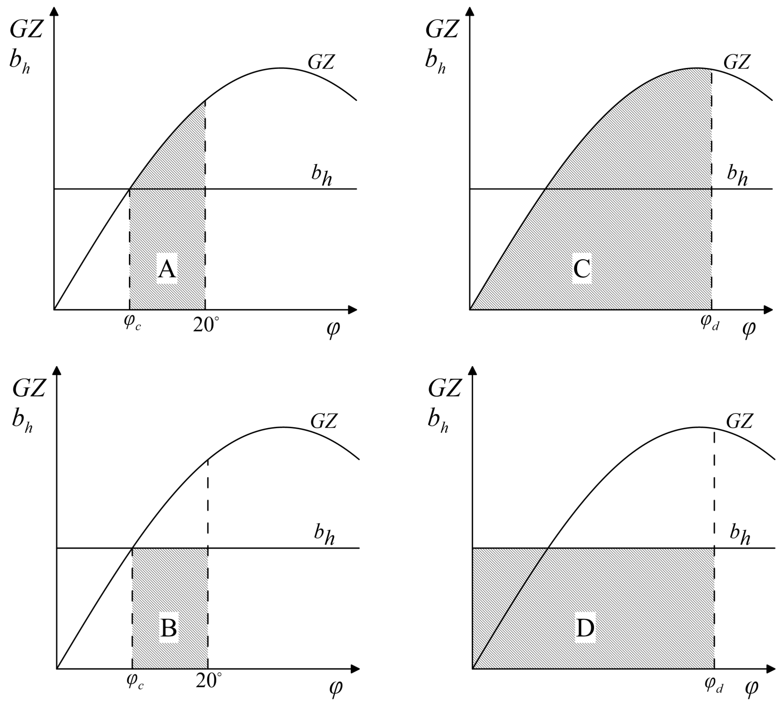

Figure 4. Harmonised escort stability criteria definition

Type C tanks are deemed as the best solutions, if their main characteristics are well optimized for the vessel in subject. In particular, considering all the design aspects and the range of capacity, the double wall technology is the best solution for the gas-propelled tug.

4. Stability during escort operations

Compared to typical ship-handling tugs, escort tugs need a higher metacentric height and more freeboard to resist the expected tow-line forces and wave build up associated with indirect towing operations. For stability, it is also important for the tow point (where the line leaves the staple) to be as low as possible; potential down-flooding points should be as high and inboard as possible. Escort tugs are generally between 28 and 40 m in length. Tugs less than 25 m may not be able to generate high enough indirect hydrodynamic forces from their hull and keel. Tugs over 45 m can generate very high escort forces but may have more difficulty managing them if they are not manoeuvrable enough. Typically tugs over 40 m in length are seldom used in ship-handling operations for this reason. Of course, the strength of the towing fittings on the escorted ship may also become a limiting factor with excessive escort forces [14]. For such a reason it is necessary to develop specific rules and requirements for escort tugs.

On this purpose, the classifications societies have issued some particular requirements, in particular with respect to stability. The guidelines take into account the variation of environmental conditions in such a way to properly define a set of service notations that clearly specify the nature of the tug operation and its operative profile [14]. The fact that multiple classification societies require different standards for the additional escort notation is not giving a clear overview of the specific requirements that need to be satisfied. For such a reason designers asked for a harmonisation of the requirements for escort tugs [15]. On this purpose, class societies have created a JIP to investigate the technical background, coherence and applicability of the existing rules for tugs [16]. The guidelines considered through the study were covering primarily the safety-related issues, such as design loads, stability, towing equipment, fire safety, life-saving appliances and safety management. As a principal outcome, in 2016 IMO adopted amendments to the 2008 Intact Stability (IS) code based on BV guidelines that will come into force in January 2020.

The key stability issues that need to be taken into consideration are the residual area under the righting arm curve, the static angle of equilibrium under heeling moment in relation to the available freeboard (crew limiting operation criteria) and the effect of waves/swell on the tow-line force. The study upon the harmonisations suggests that the approaches applied by [17,18] are the more stringent and then have been taken into account to propose the following criteria:

$$\begin{cases} A \geq 1.25B \\ C \geq 1.40D \\ f > 0 \end{cases} \tag{1}$$

Where A is the area under the righting arm curve measured from the heeling angle φ_c to 20 degrees. B is the area under the heeling arm curved evaluated from φ_c to 20 degrees. C is the area under the righting lever curve from 0 degrees to angle φ_d and D is the area under the heeling arm from 0 to φ_d as shown in Figure 4. The heeling angle φ_c represents the static equilibrium angle between heeling and righting arm considering a maximum steering force Fy, while φ_d is the minimum between the down flooding angle and 40 degrees. Parameter f is the minimum freeboard along the tug length at the heeling angle φ_c. Minimum freeboard requirement is not part of the present consideration, however, can be also considered upon the proposed additional constraint. Heeling arm curve can be obtained by full scale or model scale test, computer simulation programs (in such a case a safety coefficient should be provided to overcome uncertainties) or from a maximum Ty according to a recognised classification rule. Moreover, the heeling arm curve has to be considered constant from φ_c up to 20 degrees.

5. Equilibrium equations and hydrodynamic forces

To perform an evaluation of the maximum steering (F_S) and braking (F_B) forces that occur during escort operation it is necessary to solve a static balance equilibrium [5]. With reference to Figure 5, the static equilibrium should be granted on the horizontal and on the transversal plan, solving the following system with respect to the towing point C:

$$\begin{cases} -T_{x'} - L_{x'} + D_{x'} - F_P \cos\alpha \cos\varphi = 0 \\ -T_{y'} + L_{y'} + D_{y'} - F_P \sin\alpha \cos\varphi = 0 \\ \left(L_{y'} + D_{y'}\right) \overline{CR}_x - F_P \sin\alpha \cos\varphi \overline{CE}_x = 0 \\ -M - R + \left(L_{y'} + D_{y'}\right) \overline{CR}_z \cos\varphi - F_P \sin\alpha \cos^2\varphi \overline{CE}_z = 0 \end{cases} \tag{2}$$

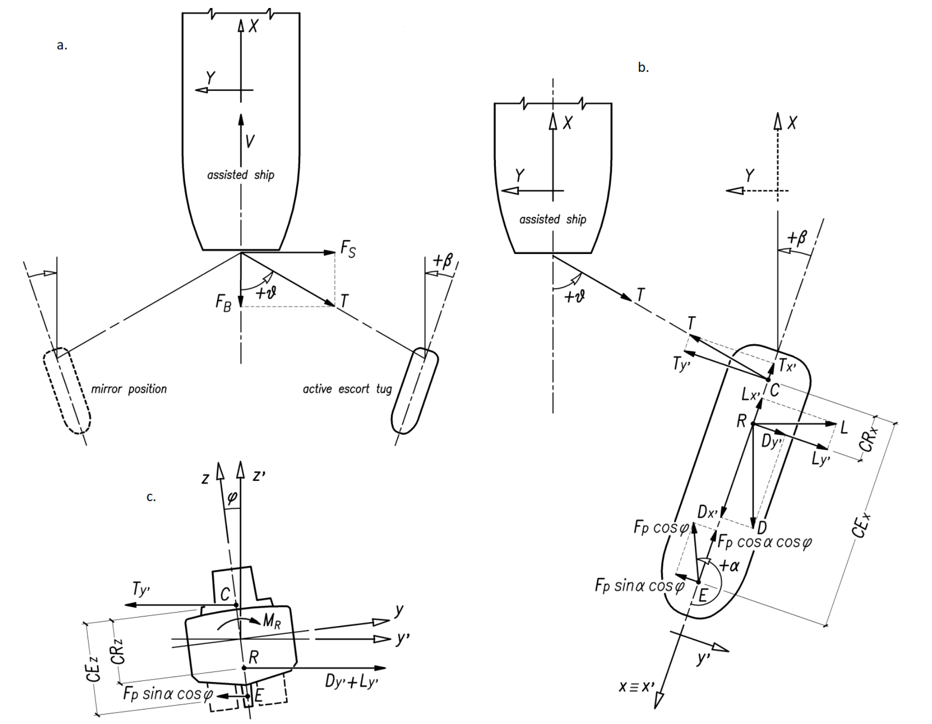

Figure 5. General reference system (a.) and forces components on horizontal (b.) and transversal (c.) plan

in which $T_{x'}$ and $T_{y'}$ are the towforce components, $L_{x'}$ and $L_{y'}$ are the lift force components and $D_{x'}$ and $D_{y'}$ are the drag force components, all with respect to the tug-fixed reference system. F_P is the force given by the propulsors, α is the direction of F_P, ϑ is the towline angle with respect to the assisted ship reference system, while M_R is the righting moment considered as a function of heeling angle φ. The tug fixed reference system is rotated of an angle β with respect to the assisted ship one; this angle is the so-called drift angle.

The lift and drag forces can be written with the following notations:

$$L = \frac{1}{2}\rho C_L A_C V^2 \tag{3}$$

$$D = \frac{1}{2}\rho C_D A_C V^2 \tag{4}$$

where ρ is the water density, V is the assisted ship speed and A_C is a characteristic area. C_L and C_D are speed independent coefficients varying with drift angle β. There are different possibilities to determine the hydrodynamic forces, starting from model test [19], CFD computations [20] or approximated methods based on wing sections equivalence [21]. Once model test are available, they should be directly used in the equilibrium determination. Model data can be considered as validation material for CFD calculations that will allow then to study the full scale scaling of the forces.

Table 1. Main characteristic of the sample VSP tug

Length overall	L_{OA}	29.38	m
Length between perpendiculars	L_{BP}	28.50	m
Breadth	B	8.80	m
Draught	T	2.40	m
Displacement	Δ	471.65	t
Vertical centre of gravity	KG	2.52	m
Bollard pull	BP	245.3	kN

6. Case study

As an indicative example, the procedure to determine the escort ability has been applied on a sample VSP harbour tractor tug, having the main characteristics as per Table 1. For this explorative study, a simple procedure has been used for the determination of the hydrodynamic forces [21]. In particular, the characteristic area A_c of equations (3) and (4) has been calculated as a function of both β and φ according to the following formulation:

$$A_c = A_L \sin\beta \cos\varphi + A_T \cos\beta + \frac{1}{2} A_H \sin\beta \sin\varphi \tag{5}$$

where A_L, A_T and A_H represent the longitudinal, lateral and horizontal area of the tug respectively.

The simulations have been performed for two different escort speed, 8 and 10 knots. Solving system (2), it was possible to determine the equilibrium conditions and towline forces as a function of the towline angle ϑ. The results ar reported in Figure 6 by means of polar diagrams. As it can be seen, the maximum towforce is changing with respect to ϑ, and consequently, also the other variables (α, β and φ) are changing. It is interesting to analyse the behaviour of φ. According to the stability criteria (1), for the selected vessel two limiting φ_c can be determined, one corresponding to 12 degrees (A/B constraint) and the other to 10.5 degrees (C/D constraint). In Figure 6 it is evident that the limits are exceeded for both the speeds once the main towforce are reached. On this purpose it has been decided to further investigate this particular situation, determining the limits in which the tug is operating respecting both, one or no criteria. In Figure 7 three different zones are highlighted, a *green* one in which the vessel can operate in safety (both criteria satisfied), a *yellow* one with can be dangerous since only one of the two stability criteria is satisfied and a *red* one were both criteria are not reached. It is the opinion that distinguish between these three modes will help the master to better control the tug behaviour during escort operations. Of course, the determination of the hydrodynamic forces adopted in this case is too simplistic and need to be improved to ensure an higher reliability of the results.

7. Conclusions

For a safe navigation in harbour or confined waters of large, potentially dangerous vessels (for instance, tankers, gas carriers, etc.) it is necessary to provide an external assistance in the manoeuvre by means of special equipped tugs. Such tugs must have the additional

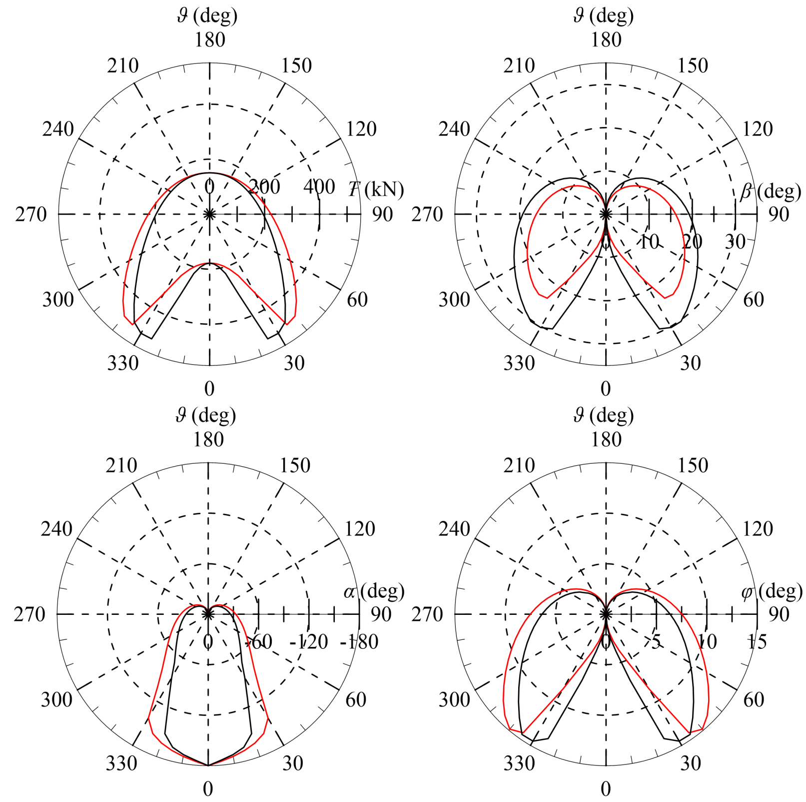

Figure 6. Escort performances and equilibrium conditions at 8 (*black*) and 10 (*red*) knots

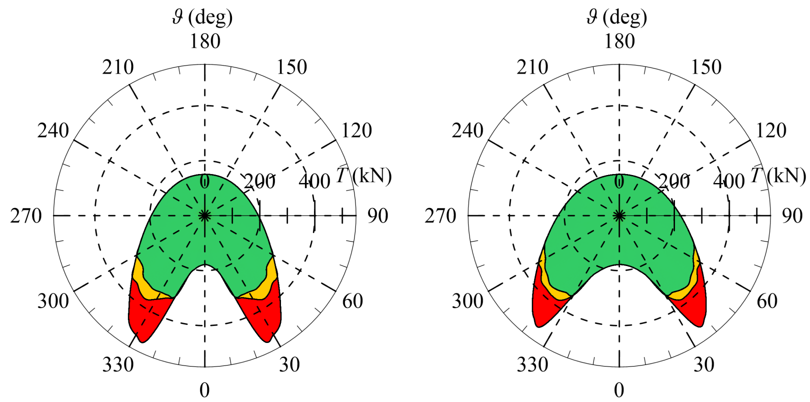

Figure 7. Safe (*green*), dangerous (*yellow*) and critical (*red*) towing conditions at 8 (*left*) and 10 (*right*) knots

escort tug notation, which can be attained either by full-scale tests or by computer model simulations. Once the tug should be propelled with liquefied natural gas, then particular attention is needed to the gas storage tank and containment system. An application of a simplified computer model simulation to a VSP tug has been carried out. All the obtained results have been collected and represented by means of polar diagrams, which can be a useful tool for the master in order to fix the different parameters involved during the escort operations. It is expected that, by increasing the accuracy of the hydrodynamic forces determination, the reliability of the final results will ensure the applicability of the procedure for existing and new tug units.

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