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ON THE CALCULATION OF THE FORCES DEVELOPED BY ESCORT TUGS

Vittorio Bucci
University of Trieste,
Department of Engineering and Architecture,
Via A. Valerio, 10, I-34127, Trieste, Italy,
E-mail: vbucci@units.it

Alberto Marino'
University of Trieste,
Department of Engineering and Architecture,
Via A. Valerio, 10, I-34127, Trieste, Italy,
E-mail: marino@units.it

ABSTRACT

Authorities and harbour operators demand tugs to assist ever-larger ships in more severe weather conditions in confined waters. The escort of such ships is carried out by specially designed tugs connected to the assisted ship by a towline in order to control course and speed of the assisted ship when it comes to sail in potentially dangerous situations, and so the risk of grounding and collision is strongly reduced. In order to achieve the "escort tug" service notation, it is necessary to predict the maximum steering forces applied on the assisted ship at different speeds. The paper deals with a method for the prediction of the escort capabilities of a tug through the quasi-steady solution of the dynamic equilibrium.

Keywords: escort, tug, computer model simulation, equilibrium prediction.

1. INTRODUCTION

Tethered escort of ships is performed by specially designed tugs linked by a towline 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 (for instance when the ship loses power and/or has low manoeuvring capabilities for the area into which it sails), to reduce 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. Figure 1 represents a statistic on ship accidents.

The escort tug improves the steering and arresting properties of the ship by means of a rope connecting the towing winch of the tug to the center bollard aft of the ship. They are equipped with a towing winch on the foredeck, and in some cases also on the aft deck, coupled with a towing fairlead (staple) located at a central position on the weather deck.

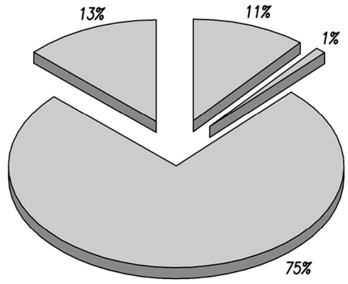

Fig. 1. Statistic on ship accidents [5]

Escort tugs have a skeg which generates a significant component of the towing force at speeds greater than 5 knots.

In harbour use, the tug can assist the ship in berthing and/or un-berthing manoeuvres.

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. The "escort tug" notation is assigned by Classification Societies for the maximum achievable steering forces, which are determined for a well defined set of speeds and in accordance with particular stability criteria. In order to establish the maximum steering forces, Classification Societies impose to carry out full-scale tests at the relevant speeds; alternatively, such forces may be evaluated by means of computer model simulations.

For new constructions, it is quite easy to perform additional tank tests to determine the lift and drag coefficients of hull and appendages as a function of the drift angle; whereas for tugs already in service, it can be more convenient to predict the escort capabilities by means of dedicated computer model programs.

In this paper is described a calculation procedure for determining the steering force of a tug during escort operations. A case study regarding a RINA-classified tug, currently in service, is presented.

2. RULES FRAMEWORK

Escort tugs are considered to be specifically engaged in steering, braking and otherwise controlling actions of ships and offshore units during navigation. They typically sail at speeds in excess of 6 knots. Escort tugs can operate in confined, sheltered waters, as well as in open sea areas. When escort tugs work from a fixed base, the crew is familiar with the area of operations, and the shoreside facilities for maintenance, repairs, spare parts, etc. are readily available. In order to consider a shoreside assistance as readily available, the tug should ensure that the ship reaches a safe sheltered anchorage within four hours at operational speed. Otherwise, if the escort tug is engaged in deep sea voyages, it is assumed that the crew is not familiar with the operating area, and shoreside facilities are in general not readily available.

On the basis of these considerations, the Certificate of Class regarding tugs specially equipped for towing and/or pushing, having equipment for escorting ships or floating units during navigation reports the following service notation: "escort tug (maximum steering force = T_{Y1} at speed V_1 and maximum steering force = T_{Y2} at speed V_2)".

The steering and braking forces are generated through the hydrodynamic forces acting on hull and appendages of the escort tug. Taken into account that the towline angle θ which is fixed at 60°, the maximum steering force T_Y comes to be the transverse component of the maximum dynamic towing pull T with respect to the centre line of the assisted ship. The latter may be obtained by full-scale tests carried out at different speeds V or, at least, at the speeds specified by the Rules. Alternatively, it is allowed to evaluate the maximum steering force T_Y by a computer model program, which considers a quasi-steady solution with all the horizontal forces and moments balanced. Specifically, the hydrodynamic forces developed by hull and underwater appendages, as well as the thrust of the propellers should be calculated.

Moreover, Classification Societies impose stability analyses for the tug, taking into account the effects on equilibrium caused by the following forces:

- Pull by the towline;
- Thrust of the propulsors;
- Hydrodynamic forces (lift and drag) of hull and appendages.

In the stability analyses, heel and trim of the tug should be considered consequent to all the acting forces during escort operations, as well as the effects of fenders, skegs, and other appendages on both reverse buoyancy and lift and drag forces. Two specific intact stability criteria are to be complied with, assuming constant heeling arms equal to the one at the equilibrium angle φ_C.

No minimum freeboard requirements are imposed, however, it is a good practice to consider the "water on deck" as an operational limit. In fact, simulation programs, in general, take into account such an event as limiting criterion for safe escort performances.

3. ASSISTED SHIP AND TOWING FITTINGS

Keeping in mind that escort tug and assisted ship cannot be considered as separate units, and taking into account that the tug plays an essential role for the overall safety, the towing equipment of the tug must comply with stringent class requirements.

Typical issues covered by the classification rules concern the material of the main shafts of the towing winches, the equipment for monitoring the pull, and the emergency quick-release systems, as well as the fendering systems.

Towing winches and hooks are to be arranged in the way of the tug's centre line, and at a proper height to minimize the heeling moments. Arrangement and scantling of towing winches and hooks should be such as not to produce any permanent deformations with the design loads.

For new constructions the breaking load of the towing equipment should be greater than the design load obtained as a function of the maximum towline force T. Whereas, for existing vessels aiming for the additional notation "escort tug", the criteria are the same, if the towing equipment already present on board remains, a check with a proper load derived from the bollard pull should be carried out.

Clearly, the design of the tug should be faced also with the strength characteristics of the pieces of equipment (bollards, winches, supporting hull structures, etc.) of the ships which need escorting.

As for the towing equipments installed on the assisted ship, they should comply with the following rules and guidelines:

- SOLAS Ch. II-1 Reg. 3-8, Towing and mooring equipment [9];
- IACS Unified Requirements UR A2, Shipboard fittings and supporting hull structure associated with towing and mooring on conventional vessels [4];
- Classification Society Rules, specific prescription for obtaining the additional class notation "ESCORT TUG" [3] [7];
- OCIMF (Oil Companies International Marine Forum), Mooring equipment guidelines.

For escort operations, the IACS UR A2 defines the design load as equal to the nominal breaking load of the towline. Consequently, the Safe Working Load (SWL) of the equipment present on the assisted ship should be consistent with such a breaking load.

Therefore, if a ship is intended to be escorted by a tug, the strength (that is to say the Safety Working Load, SWL) of the towing fittings present on board must be properly established in accordance with the pull capacity of the tug called for escorting, because the scantling based on the equipment number of the ship could be insufficient.

4. ESCORT TUG CONFIGURATIONS

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).

The two most popular types are the Tractor-tugs (with either Azimuthal or Voith-Schneiner propeller) and the Azimuthal-Stern-Drive tugs (ASD-tugs). Their peculiar distinctive mark is the position of the propulsors at the bow (Fig. 2) or at the stern (Fig. 3), respectively.

In addition, the hull forms adopted for Tractor-tugs and ASD-tugs are significantly different. Both hull form types have undergone important optimizations during the last years, so that new designs have been developed, such as the Rotor Tugs having two azimuthal propellers at the bow and one at the stern (Fig. 4), and the Ship Docking Modules characterized by a double-ended hull form, and propelled by one azimuthal drive at the bow on starboard side and another at the stern on portside (Fig. 5).

Which type of tug is to be used depends on the requests of the operators. It should be considered that a large towing force can be attained by the contribution of both the thrust of the propulsors and the lift and drag generated by hull and appendages. During escort operations, the tug should be positioned in such a way to develop the highest resistance possible through the steerable thrusters, so that the tug works as a remote rudder behind the assisted ship.

The different modes used by a tug during escort can be synthesized as follows:

- Indirect towing – the tug uses its thrust to maintain a sheered position with respect to the towline, and the pull is essentially supported by the drag and lift generated by the hull (Fig. 6).
- Direct towing – in this mode the speed is very low and the thrust of the tug is almost aligned with the towline (Fig. 7).
- Reverse arrest – the towline pull develops only the braking component; the tug is aligned with the centre line of the assisted ship and the thrust is backwards (Fig. 8).
- Transverse arrest – the azimuthal drives of the tug are placed athwart, in order to produce opposite thrusts (Fig. 9).

The objective of escorting is to provide maximum braking and steering forces at usual escorting speeds of 8 or 10 knots. Which mode is more suitable to carry out the escort service depends on different parameters: the intended manoeuvre to be performed, the effective time of reaction, the hydrodynamic behaviour of the hull, the obtainable thrust in accordance with the characteristics of both the engine and the propellers. In addition, it is very important to shift the tug from an equilibrium position at a side to the mirror position as fast as possible, in analogy with a conventional rudder of a ship.

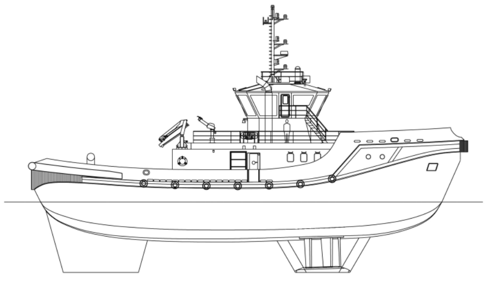

Fig. 2. Voith-Schneider-Propelled tug (VSP-tug)

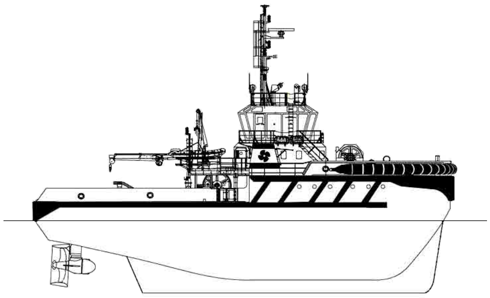

Fig. 3. Azimuthal-Stern-Drive tug (ASD-tug)

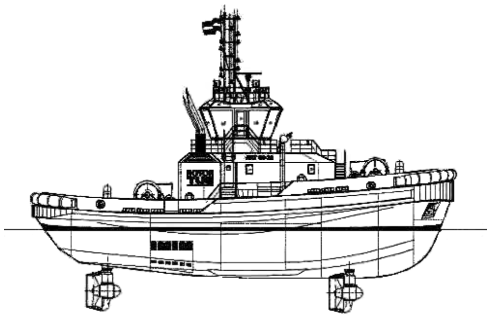

Fig. 4. Rotor Tug

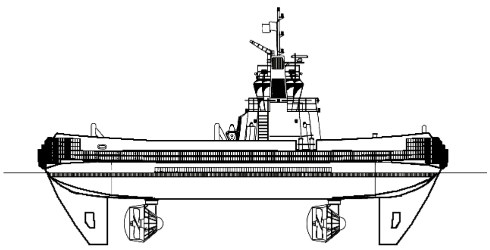

Fig. 5. Ship Docking Module

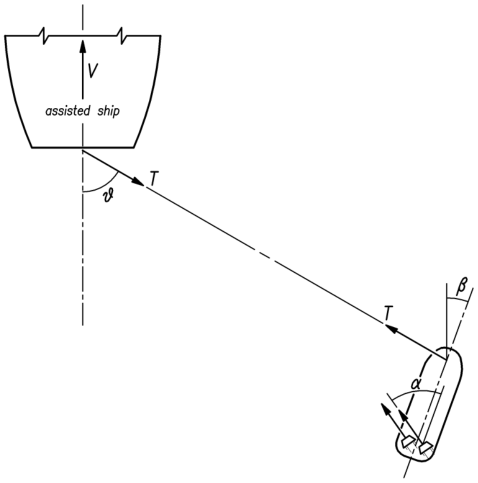

Fig. 6. Configuration during the indirect towing

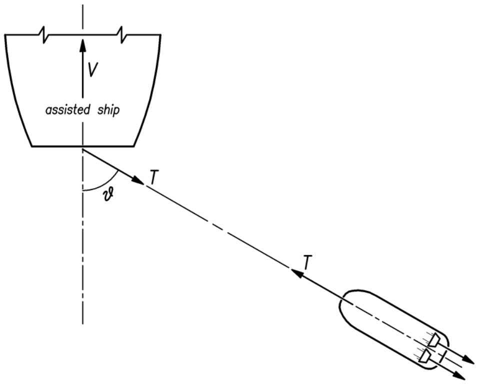

Fig. 7. Configuration during the direct towing

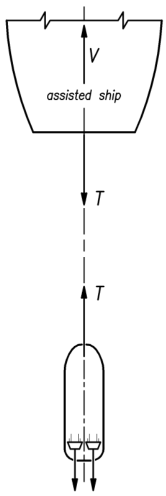

Fig. 8. Configuration during the reverse arrest

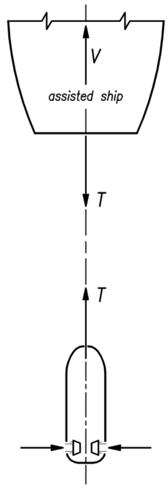

Fig. 9. Configuration during the transverse arrest

5. EQUILIBRIUM EQUATIONS

In order to analyze the escort performances of a tug during the assistance to a vessel, it is necessary to solve essentially a problem of balance.

The mutual position between tug and assisted vessel is sketched in Figure 10. The tug is in a condition of equilibrium when it advances at the same speed V of the assisted vessel with an oblique angle β (drift) between the direction of V and the tug's centre line. Two right-handed reference systems are considered: the XYZ fixed with the assisted ship and the xyz fixed with the escort tug. A further $x'y'z'$ reference system for the tug is introduced, where the $x'y'$-plane parallel to the waterplane is obtained just by rotating the xy-plane by the heel angle φ.

Figures 11 and 12 show the components of the forces applied to the tug with reference to the horizontal $x'y'$-plane and to the transverse $y'z'$ -plane, respectively.

Specifically, the forces acting upon the tug during the escort operations are:

- Lift force L of hull and appendages;
- Drag force D of hull and appendages;
- Overall thrust F_P of the propulsors;
- Pulling force T exerted by the towrope.

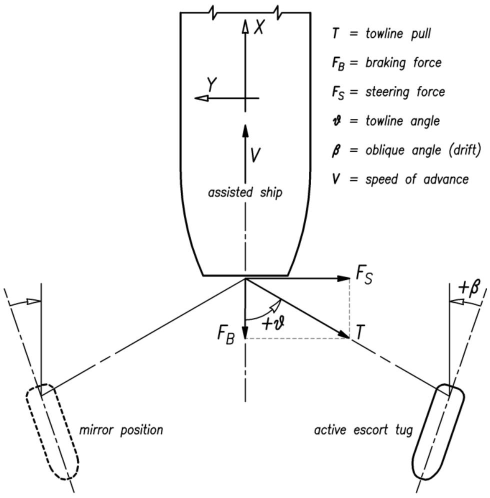

Fig. 10. Position of the tug during indirect towing

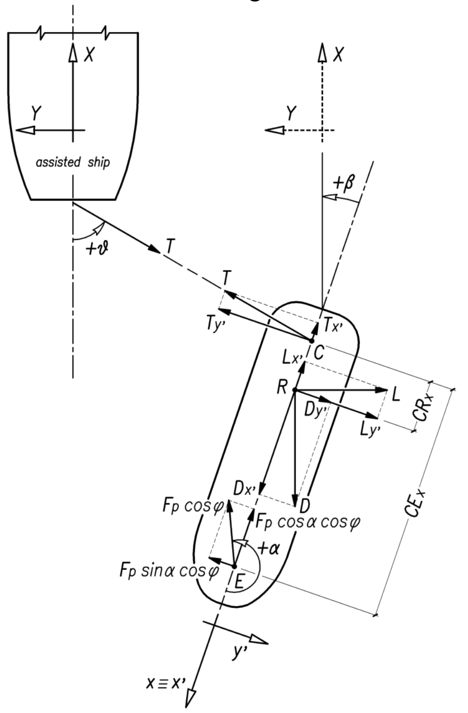

Fig. 11. Force components in the horizontal plane

For the equilibrium analysis of the tug, the components of such forces with respect to $x'y'z'$ reference system are considered. The direction of the towrope pull T is assumed to be parallel to the waterplane due to the great distance between the assisted ship and the escort tug. Moreover, aft of the assisted ship, T is resolved in the two components F_S (steering force) and F_B (braking force), in order to stress the action of the tug on the ship itself.

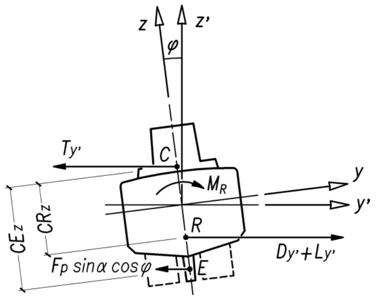

Fig. 12. Force components in the transverse plane

The components of the forces are considered positive when they act in the positive coordinate direction, whereas angles are positive if counter-clockwise in a positive face (i.e., a face whose outward normal is along the positive direction of a coordinate axis).

The evaluation of the steering force F_S passes through the balance analyses of forces and moments acting in both the horizontal and the transverse planes. In fact, with reference to the forces indicated in Figure 11 and 12, the following equations can be set up:

- Balance of the forces acting in the x'-direction:

$$-T_{x'} - L_{x'} + D_{x'} - F_P \cos\alpha \cos\varphi = 0 \quad (1)$$

- Balance of the forces acting in the y'-direction:

$$-T_{y'} + L_{y'} + D_{y'} - F_P \sin\alpha \cos\varphi = 0 \quad (2)$$

- Balance of moments acting in the $x'y'$-plane with respect to point C:

$$\left(L_{y'} + D_{y'}\right) CR_x - F_P \sin\alpha \cos\varphi \, CE_x = 0 \quad (3)$$

- Balance of moments acting in the $y'z'$-plane with respect to point C:

$$-M_R + \left(L_{y'} + D_{y'}\right) CR_z \cos\varphi - F_P \sin\alpha \cos^2\varphi \, CE_z = 0 \quad (4)$$

where $M_R = \Delta g GZ$ is the righting moment, function of the heel angle φ.

6. HYDRODYNAMIC FORCES OF THE TUG'S HULL

The lift and drag forces are defined as:

$$L = \frac{1}{2}\rho C_L A_C V^2 \quad (5)$$

$$D = \frac{1}{2}\rho C_D A_C V^2 \quad (6)$$

where: ρ is the water density; C_L is the lift coefficient; C_D is the drag coefficient; V is the water free-stream velocity (equal to the ship speed); A_C is the characteristic area (further defined). As for the area A_C, conventionally it is used the wetted area for surface ships, the frontal area for stubby bodies such as cylinders, cars or torpedoes, and the planform area for wings and hydrofoils. Since the escort tug is moving through the water at a non-zero angle of attack, its resistance is primarily composed of pressure drag (or form drag), and consequently the tug behaves more like a stubby body rather than a typical slender hull of a surface ship, where frictional drag has a dominant role [11]. Therefore, hydrodynamic forces developed by both the hull and appendages of the tug have been globally evaluated likewise a stubby body, taking as characteristic area A_C the wetted area of hull and appendages projected in the direction of the speed V (i.e., X-axis) on the vertical YZ-plane, that is to say the so-called frontal area. Figure 13 shows a possible plot of lift and drag coefficients vs the oblique (drift) angle derived from full-scale tests for a VSP tug.

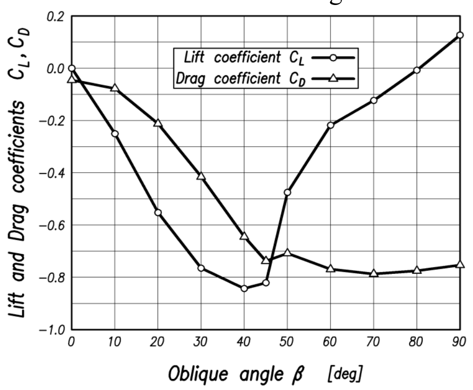

Fig. 13. Lift and Drag coefficients for a VSP tug [8]

7. CASE STUDY

The above-exposed procedure has been applied to an existing VSP harbour tractor tug, built in 1972, which recently has achieved the additional class notation "escort tug" by RINA.

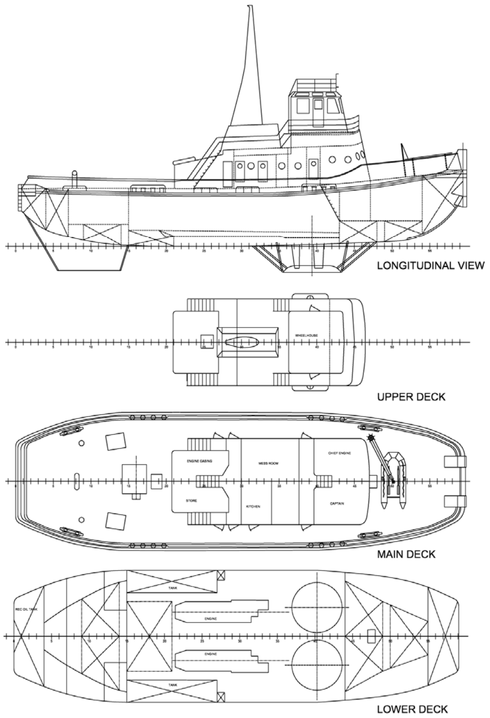

Fig. 14. VSP tug of the case study

The general arrangement of the tug is shown in Figure 14, while Table 1 collects its main characteristics.

Table 1. Main characteristics of the tug

Length overall	$L_{OA} =$	29.38 m
Length between perpendiculars	$L_{BP} =$	28.50 m
Breadth	$B =$	8.80 m
Depth	$D =$	3.60 m
Loadline draught	$T =$	2.40 m
Displacement (mass)	$\Delta =$	471.65 t
Engine power	$P =$	2×736 kW
Maximum speed	$V =$	12.5 kn
Bollard Pull	$BP =$	245.3 kN
Gross Tonnage		243 GT
Classification Society	RINA	

For the evaluation of the escort capability of the considered tug, it is essential to fix as reference loading condition the most frequent one that is foreseen to exert the escort service, Table 2.

Table 2. Reference loading condition of the tug

Displacement (mass)	$\Delta =$	447.01 t
Lightship weight	$LSW =$	356.61 t
Deadweight	$DWT =$	90.40 m
Longitudinal centre of gravity	$LCG =$	14.551 m
Transversal centre of gravity	$TCG =$	0.000 m
Vertical centre of gravity	$VCG =$	2.519 m
Draught at the centre of flotation	$T_O =$	2.720 m
Draught aft	$T_A =$	2.680 m
Draught forward	$T_F =$	2.760 m
Static trim	$t_S =$	-0.080 m
Longitudinal centre of flotation	$LCF =$	14.090 m
Longitudinal centre of buoyancy	$LCB =$	14.490 m

The characteristic area A_C to be used in the calculation of lift and drag forces (formulae 5 and 6), in the exposed methodology, corresponds to the frontal area of the wetted body, and has been calculated as a function of both the heel angle φ and the drift angle β, considering the different components of the wetted area both of hull and appendages. Specifically, such components are obtained projecting the wetted area on the *xyz*-coordinate planes. So that, if A_L, A_T and A_H represent the longitudinal, transversal and horizontal area respectively, the frontal area A results:

$$A_C = A_L \sin\beta \cos\varphi + A_T \cos\beta + \frac{1}{2} A_H \sin\beta \sin\varphi \tag{7}$$

The horizontal area A_H is given mainly by the area of the bottom, and the factor 1/2 in the above formula (7) is a simplification in order to consider the hidden area due to the high deadrise angle of the bottom.

The lift and drag coefficients have been assumed as in Figure 13, and are derived from full-scale tests carried out by Ratcliff [6] and Smoker [8].

As required by the RINA's classification rules [7], two different simulations have been performed, considering a speed of the assisted ship equal to 8 and 10 knots, respectively.

Taking into account that the tug is an existing vessel, the maximum towline pull T has been limited to the bollard pull, in order not to modify the towing equipment already installed on board.

The results of the equilibrium analyses for a towline angle θ = 60 deg (the maximum allowed by Regulations) are reported in Table 3 and 4, where is also highlighted the fulfilment of the stability criteria in terms of the areas A, B, C and D related to the righting and the heeling arm curves.

Table 3. Equilibrium at 8 knots

Speed	$V =$	8 kn
Towline pull	$T =$	247.4 kN
Thrust of the propulsors	$F_P =$	164.9 kN
Towline angle	$\vartheta =$	60 deg
Oblique angle (drift)	$\beta =$	19.0 deg
Heel angle	$\varphi =$	7.1 deg
Thrust angle	$\alpha =$	203.9 deg
Steering force	$F_S =$	214.2 kN
Stability criterium ($A/B \geq 1.25$)	$A/B =$	1.825
Stability criterium ($C/D \geq 1.40$)	$C/D =$	2.124

Table 4. Equilibrium at 10 knots

Speed	$V =$	10 kn
Towline pull	$T =$	247.2 kN
Thrust of the propulsors	$F_P =$	119.0 kN
Towline angle	$\vartheta =$	60 deg
Oblique angle (drift)	$\beta =$	4.0 deg
Heel angle	$\varphi =$	7.0 deg
Thrust angle	$\alpha =$	213.3 deg
Steering force	$F_S =$	214.1 kN
Stability criterium ($A/B \geq 1.25$)	$A/B =$	1.854
Stability criterium ($C/D \geq 1.40$)	$C/D =$	2.169

By means of such simulations, the considered tug has achieved the following additional class notation: ESCORT TUG (8, 214 – 10, 214).

The equilibrium analyses, for a given speed, have been systematically carried out for a certain towline angle θ by varying the oblique angle β until the towline pull T turns

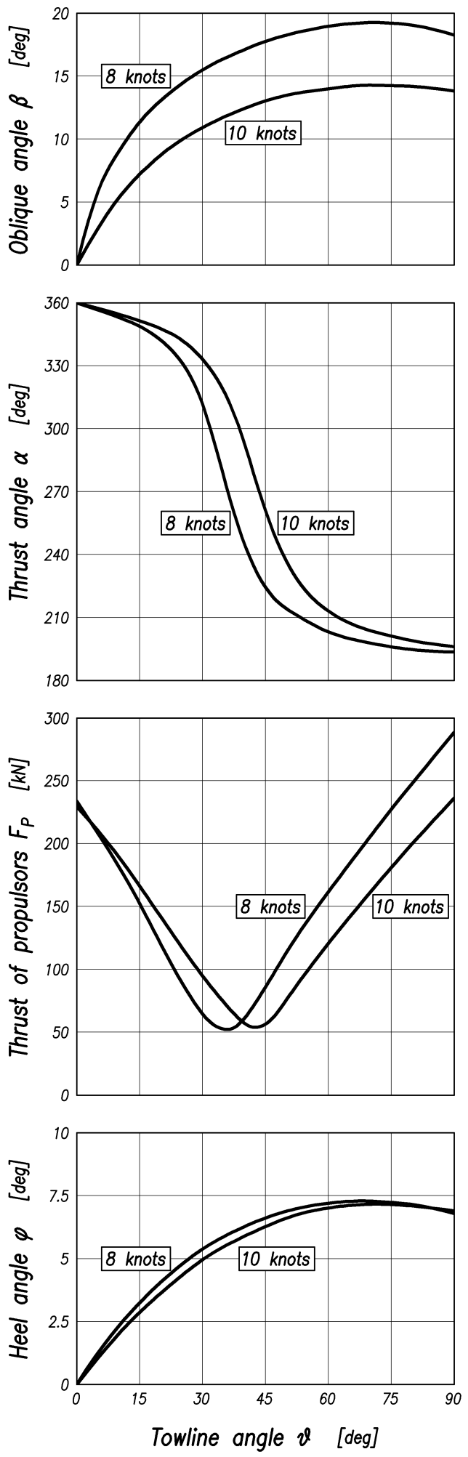

Fig. 15. Results at equilibrium vs towline angle θ

to be as close as the bollard pull. The complete results drawing from the above described equilibrium analyses are shown in the graphics of Figure 15. In particular, for the two reference speeds of 8 and 10 knots, the oblique angle β of the centerline of the tug with respect to the advance direction, the thrust angle α as given by the orientation of the two propulsors (in accordance with the convention reported in Figure 11), the total thrust force F_P of the propulsors and the heel angle φ at the equilibrium are plotted versus the towline angle θ. The range considered for θ is from 0 to 90 deg, but it has to be considered that during escort operations the value θ = 60 deg must not be exceeded.

8. 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 specially equipped tugs. Such tugs must have the additional class notation "escort tug", which can be attained either by full-scale tests or by computer model simulations. In this paper a calculation procedure has been presented in order to find the equilibrium condition during the escort operations, and to determine the geometric configuration of the tug along with all the forces involved. The hydrodynamic coefficients for lift and drag have been assumed in accordance with the findings of researches available in open literature.

An application of the proposed computer model simulation to an existing VSP tug has been carried out. All the results obtained have been collected and represented by curves, which can be a useful tool for the master in order to fix the different parameters involved during the escort operations.

REFERENCES

[1]. **Aryszuk J.,** "*Steady-state Manoeuvring of a Generic ASD Tug in Escort Pull and Bow-rope Aided Push Operation",* Transnav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 8, N. 3, September 2014.

[2]. **De Jong G. T.**, "*The Class Answer to the Rapidly Developing Tug Industry"*, Proceedings of ITS, Toulon, 2010.

[3]. **Germanisher Lloyd**, "*Rules for the Classification and Construction"*, Pt. 1 Ch.1 Sec. 25, 2015.

[4]. **IACS**, "*Unified Requirements UR A2, Shipboard fittings and supporting hull structure associated with towing and mooring on conventional vessels"*, 2007.

[5]. **Northern Gateway Pipelines Limited Partnership**, "*B 23-20, Appendix A TERMPOL TDR Maneuvering Study of Escorted Tankers Part 2 Main Report",* FORCE Technology., 2011.

[6]. **Ratcliff A. J. T.**, "*A study of the hydrodynamic performance of Voith-Schneider propelled escort tugs",* University of British Columbia, 2003.

[7]. **RINA**, "*Rules for the Classification of Ships"*, Pt. E Ch. 14, 2015.

[8]. **Smoker B.**, **"***Escort Tug Performace Prediction: A CFD Method"*, University of Victoria, 2012.

[9]. **SOLAS**, "*Towing and mooring equipment"*, Ch. II-1 Reg. 3-8, IMO 6th edition, 2014

[10]. **Van Kasteren J**.,*" The ART of tugnology: the ultimate balance between safe ship assist and safe escorting duties"*, ROTORTUG, 2012**.**

[11]. **White F. M**., *"Fluid Mechanics"*, MacGraw-Hill, 2006.

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