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Steady-state Manoeuvring of a Generic ASD Tug in Escort Pull and Bow-rope Aided Push Operation

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ABSTRACT: This paper is devoted to expand the very promising research undertaken in the author's previous work, basically done on simplified modelling the escort push operation. Now, the other two modes of a tug's employment, as stated in the title, are covered. The special focus is again set on the indirect towing in that the towline force is much higher than the thruster force. The ratio of these two forces, referred to as the relative towing force (or amplification ratio) is evaluated together with the hull drift angle and the thruster(-s) angle for a given escort speed. This mutual relationship is known as the tug performance diagram. Although rather generic (container-type) formulas are derived, they are supplied for exemplification purposes with simple, analytically given hull hydrodynamic forces. The aim is also here to provide a basis for further sensitivity analysis of the model and possible improvement/optimisation to the tug design. The obtained charts also could serve as rough and clear guidance for towmasters while escorting.

1 INTRODUCTION

For safe and efficient ship-tug operation from the viewpoint of a tug's master (towmaster) we need to have exact knowledge and understanding of the complex relationship between multiple input control variables and the output performance of a tug. The output performance, ordered by a pilot and/or captain, is mostly indicated by the towing force (in terms of direction and magnitude) applied on the towed ship. This force is transferred by a hawser (towing line) in pulling mode or a direct hull contact in pushing mode. Especially in pulling mode, the towing force can be decomposed, into the steering/transverse and backing/longitudinal components – both directions are taken with respect to the assisted ship. On the other side, the required tug's control parameters, primarily consisting of three variables: the hull drift angle, the thruster angle and force, essentially change with the speed of the assisted ship. In addition, for medium and high speeds of the escort operation tugs apply the so-called indirect towing in that they can take advantage of the hydrodynamic force developed on their underwater hull. This way the effective towing force is much higher than the thruster force.

Since there are some specific, more precise definitions within industry, we simply consider the focused ASD tug as a tug with the directional propulsion located aft and the towing point forward. By statistics [Artyszuk, 2013b], this will mostly be an azimuthing (podded, z-drive) propulsion tug, and mainly with dual propulsors installed symmetrically versus a tug's centre plane for independent operation. However, this paper is essentially dealing with indirect towing performed by a parallel/coupled operation of both propulsors, so they can be regarded as a single unit of twice increased power, which is through the text uniquely called as the thruster.

Because we are implementing rather general hydrodynamic model of the thruster, the results can be easily adopted to another types of directional propeller, e.g. the Voith-Schneider propeller (VSP), even when these are installed in the forward part of a tug (called then a tractor tug), as usual for this propulsion. In the latter case of a tractor tug, we have to remember that this tug will also work/assist by its end, which is free of the thrusters, i.e. by the stern, quite similar to ASD tugs acting through the bow.

Some research centres, refer e.g. to [Hensen, 2003], [Quadvlieg, Kaul, 2006], [Renilson et al., 1992], [Waclawek, Molyneux, 2000], claim they developed a software for computing tow forces, as well as the necessary control parameter values on a tug, in steady state situations. However, appropriate results and discussion concerning both the applied mathematical model and the detailed, well documented output in the form of charts are practically not published. If any, such diagrams are sometimes very hard in handling.

Under such background the author's conducted a research on the mechanism of equilibrium for a tug in the escort operation, i.e. the towing assistance rendered under significant speed of the assisted ship. The study preliminarily involved the case of pushing operation [Artyszuk, 2013a]. The reader is encouraged to refer to this work which is available in open-access through the web-site of the author's affiliation. Now, in the present paper, those analytical solutions are being generalised to cover a more sophisticated case, namely the pulling mode. Under appropriate parameter values, the presented hereafter solution converges to the previous pure pushing mode. At the end of paper, however, some considerations are also made with regard to applying the results to pushing mode with bow-line support or the friction effect included.

2 MATHEMATICAL MODEL

The ship-tug arrangement during the so-called indirect pulling operation, together with forces and conventions for angles, is presented in Figure 1. The indirect towing involves taking advantage of a tug's underwater hull hydrodynamic force while rendering assistance at significant escort speed. The tug-fixed coordinate system *Mxy* is positioned for convenience at the intersection of her centre plane and midship section, with *x* axis pointing forward and *y* axis to starboard side.

The equilibrium conditions for a tug between the hull (*H*), thruster/propeller (*P*), and towing (*T*) forces in tug's coordinates take the form:

$$\begin{cases} F_{xH} + F_{xP} + F_{xT} = 0 \\ F_{yH} + F_{yP} + F_{yT} = 0 \\ M_{zH} + M_{zP} + M_{zT} = 0 \end{cases} \tag{1}$$

where:
F_x, F_y – longitudinal and lateral components of each force [N],
M_z – moment developed by particular force [Nm].

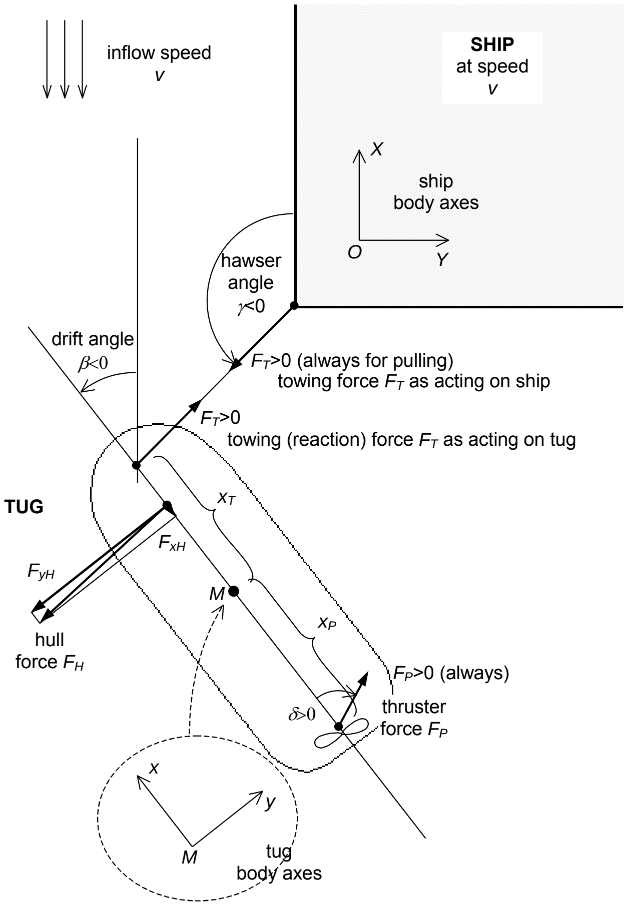

Figure 1. Definition sketch of forces and angles in tug's dynamics

The hull moment M_{xH} is specific in that it is directly measured or computed, and published, and is being rarely based on constructing the product of the hull lateral force F_{yH} and an abscissa of its application point, which is also sometimes called an arm or lever. The latter is namely generally out of interest in hull hydrodynamics.

The tug hull hydrodynamic forces are commonly written as follows:

$$\begin{bmatrix} F_{xH} \\ F_{yH} \\ M_{zH} \end{bmatrix} = 0.5\rho L T v^2 \cdot \begin{bmatrix} c_{fxh}(\beta) \\ c_{fyh}(\beta) \\ L \cdot c_{mzh}(\beta) \end{bmatrix} \tag{2}$$

where:
ρ – water density [kg/m^3],
L, T – tug's length (between perpendiculars) and draft (extreme) [m],
v – absolute inflow speed (equal to the escort speed) [m/s],
c_{fxh}, c_{fyh}, c_{mzh} – nondimensional hydrodynamic coefficients [–],
β – drift angle (equal to tug's inclination angle vs. ship's hull) [°].

The hull hydrodynamic coefficients for rectilinear, oblique motion, as in case of our static conditions, are functions of the drift angle and usually lookup-table stored. The lookup-table approach is also an essential part of the developed and hereafter presented algorithm for solving the equilibrium condition. However, in view of the undertaken preliminary research some simple, analytical, and qualitative relationships are introduced to such tables:

$$\begin{aligned} c_{fxh}(\beta) &= -0.03\cos\beta \\ c_{fyh}(\beta) &= +0.5\sin\beta \\ c_{mzh}(\beta) &= +0.1\sin 2\beta \end{aligned} \tag{3}$$

where $\beta \in \left(-180°, +180°\right\rangle$.

Due to symmetry and for some practical reasons connected with physically justified equilibrium conditions, we will seek the equilibrium solution in the range of negative drift angles (β<0), strictly for $\beta \in \left\langle -90°, 0°\right)$. This corresponds to a tug secured on the ship's port quarter and facing its starboard bow towards the inflow, as shown in Figure 1.

In view of getting an equilibrium solution, the ratios of tug hull hydrodynamic coefficients turn to be very useful:

$$c'_{fxh}(\beta) = \frac{c_{fxh}(\beta)}{c_{fyh}(\beta)}, \qquad c'_{mzh}(\beta) = \frac{c_{mzh}(\beta)}{c_{fyh}(\beta)} \tag{4}$$

The graphical image and detailed discussion of these relationships is contained in [Artyszuk, 2013a].

The thruster forces and moment in (1) read:

$$\begin{bmatrix} F_{xP} \\ F_{yP} \\ M_{zP} \end{bmatrix} = F_P \begin{bmatrix} \cos\delta \\ \sin\delta \\ x_P \cdot \sin\delta \end{bmatrix} \tag{5}$$

where:
F_P – absolute value of thrust (always positive) [N],
δ – thruster angle (equal to the thrust angle) [°],
x_P – thruster position (negative in aft direction) [m].

Though most harbour tugs have dual, independent propulsors to enhance their manoeuvrability, it is assumed in the present study, as mentioned before, that both thrusters rotate parallel and work equally. This means we can adopt a single thruster of twice increased force. Additionally, the advance speed effect on the thruster performance loss and the influence of local drift angle on producing the lateral component of the thruster force are disregarded in this preliminary investigations. So, both symbols F_P and δ are denoting the effective thruster force and its direction angle.

The towing (pull) force, as the reaction force excited on a tug, according to the conventions adopted in Figure 1, i.e. with full support of sign, is described by:

$$\begin{bmatrix} F_{xT} \\ F_{yT} \\ M_{zT} \end{bmatrix} = -F_T \begin{bmatrix} \cos(\gamma-\beta) \\ \sin(\gamma-\beta) \\ x_T \cdot \sin(\gamma-\beta) \end{bmatrix} \tag{6}$$

where:
F_T – absolute value of towing force (always positive) [N],
γ – hawser angle (negative when leading to portside of the towed ship) [°],
x_T – towing point position (positive in forward direction) [m].

3 ANALYTICAL SOLUTION OF THE EQUILIBRIUM

Identically to [Artyszuk, 2013a], one can easily find that:

$$c'_{fxh}(\beta) = \frac{-\cos\delta + F'_T\cos(\gamma-\beta)}{-\sin\delta + F'_T\sin(\gamma-\beta)} \tag{7}$$

$$c'_{mzh}(\beta) = \frac{-x'_P\sin\delta + x'_T F'_T\sin(\gamma-\beta)}{-\sin\delta + F'_T\sin(\gamma-\beta)} \tag{8}$$

where we have defined the relative towing force F'_T, as being as the ratio of the thruster force:

$$F'_T = \frac{F_T}{F_P} \tag{9}$$

and the other nondimensional quantities connected with the geometrical positions of towing point and the thruster:

$$x'_T = \frac{x_T}{L}, \quad x'_P = \frac{x_P}{L} \tag{10}$$

In the exemplary calculations presented in the next chapter we are assuming:

$$x'_T = +0.5L, \quad x'_P = -0.5L \tag{11}$$

The formulas (7) and (8) can be converted into:

$$F'_T = \frac{-\cos\delta + c'_{fxh}(\beta)\cdot\sin\delta}{-\cos(\gamma-\beta) + c'_{fxh}(\beta)\cdot\sin(\gamma-\beta)} \tag{12}$$

$$F'_T = \frac{\sin\delta}{\sin(\gamma-\beta)}\cdot\frac{-x'_P + c'_{mzh}(\beta)}{-x'_T + c'_{mzh}(\beta)} \tag{13}$$

Making both them equal, we are arriving at the first (starting) fundamental relationship $\delta = \delta(\beta, \gamma)$, where γ is the parameter:

1° $$\boxed{\tan^{-1}\delta = F'_T = \frac{-x'_P + c'_{mzh}(\beta)}{x'_T - c'_{mzh}(\beta)}\left[-\tan^{-1}(\gamma-\beta) + c'_{fxh}(\beta)\right] + c'_{fxh}(\beta)} \tag{14}$$

The direct equation (14), explicit vs. thruster angle δ, shall be solved in the drift angle domain. So, for a series of discrete values of the drift angle β we are computing the corresponding values of the balancing thruster angle δ.

The second fundamental equation is one of the two equivalent formulas: (12 or (13). Both make a dependence of the relative towing force $F_T^{'}$ on the just determined thruster angle δ. Below the latter formula is being chosen:

$$2° \quad \boxed{F_T^{'} = \frac{\sin\delta}{\sin(\gamma-\beta)} \cdot \frac{-x_P^{'} + c_{mzh}^{'}(\beta)}{-x_T^{'} + c_{mzh}^{'}(\beta)}} \qquad (13)$$

The third fundamental expression in the sequence of our computations consists of the balance equation for lateral forces, see (1):

$$3° \quad \boxed{F_{yH}^{'} = -\sin\delta + F_T^{'}\sin(\gamma-\beta)} \qquad (15)$$

where we have defined the relative hull lateral force $F_{yH}^{'}$ in the similar way to $F_T^{'}$ in (9):

$$F_{yH}^{'} = \frac{F_{yH}}{F_P} \qquad (16)$$

The relationship (15) takes on input the previously established values of δ and $F_T^{'}$.

Finally, we use the middle formula in (2) to relate the escort speed to the absolute magnitude of the thruster force F_P in the form of:

$$4a° \quad \boxed{v = \sqrt{\frac{F_{yH}^{'} \cdot F_P}{0.5\rho LTc_{fyh}(\beta)}}} \qquad (17a)$$

or

$$4b° \quad \boxed{F_P = \frac{0.5\rho LTv^2 c_{fyh}(\beta)}{F_{yH}^{'}}} \qquad (17b)$$

Four fundamental equations (14), (13), (15), and (17) constitute the basic mechanism of the wanted tug's equilibrium.

4 NUMERICAL RESULTS

For below computations we adopt the following conditions of the environment and the tug: water density 1000kg/m^3, L=30.5m, T=5m.

Figure 2 presents the basic computation results of our formulas. Two different, rather extreme and thus meaningful thruster force values F_P have been here selected, corresponding to 50t and 10t. The unit of tonne has been here consciously taken, since this still serves as the industry language of evaluating tug capabilities and conducting towing operations. Figure 2 is comprising four sub-charts for each case of the F_P magnitude. They show accordingly: the thruster angle δ, drift angle β (in some studies referred to as the yaw or slip angle), the relative hull lateral force $F_{yH}^{'}$, and finally the most important relative towing force $F_T^{'}$. They are plotted versus the escort speed. The typical range of speed is included, i.e. up to about 10 knots. The hawser angle γ is the parameter for all the curves, $\gamma \in \langle -180°, -90° \rangle$, though its name only appears for the top-level subdiagrams. The value of γ corresponding to –180° means a hawser in the centre plane and aft direction of the assisted ship, while –90° marks the hawser set abeam of the ship, also refer to Figure 1.

The excellent indirect towing performance is achieved for the lower thruster force, since for the tug hull size of order 30m in length (the typical dimension of a harbour tug) and the investigated escort speeds much of the equilibrium is relatively dominated by the tug hull hydrodynamic force. It shall be mentioned that both columns of Figure 2 are essentially similar to each other in that the adopted thruster force is causing the horizontal scaling (multiplying the 'x-values') of the charts.

In case of γ= –90° we are receiving the same results as for pushing operation which were published in [Artyszuk, 2013a].

For some hawser directions we may find even up to three different equilibrium solutions in terms of thruster angle and drift angle. Those are of course accompanied by a different relative towing force contributing to an effective tug's pull force rated in tonnes.

In Figure 3 there is shown a mutual relationship of the thruster and drift angles. As clear from Equation (14), it is neither influenced by the thruster absolute force, nor the escort speed. The curve for γ= –90° in the vicinity of zero drift angle slightly differs from that in [Artyszuk, 2013a]. This small discrepancy is due to a better discretization (lookup-table based interpolation) of the tug hull hydrodynamic coefficients for the purpose of the present study.

The relative towing force $F_T^{'}$ can be decomposed for a practical application in ship towing operations into the backing and steering components. This way, they are also expressed as the relative quantities, i.e. compared versus the thruster force:

$$F_{back}^{'} = F_T^{'}\cos\gamma\,, \quad F_{steer}^{'} = F_T^{'}\sin\gamma \qquad (18)$$

Both are demonstrated in Figure 4. For the higher thruster force 50t, they are generally hardly effective (note the values less than unity).

The subsequent Figure 5 comprises the results of calculation of the required thruster force (absolute one in tonnes) for a given escort speed, see Equation (17b). Of course, Figure 5 repeats to some extent the data of Figure 2. Nevertheless, it provides data in a different format, discretization, and is very useful to directly study the thruster force under input escort speed. Only three distinct hawser directions are considered: –90° (steering action only) –135° (equal backing and steering action), and steering action only, –180° (backing action only).

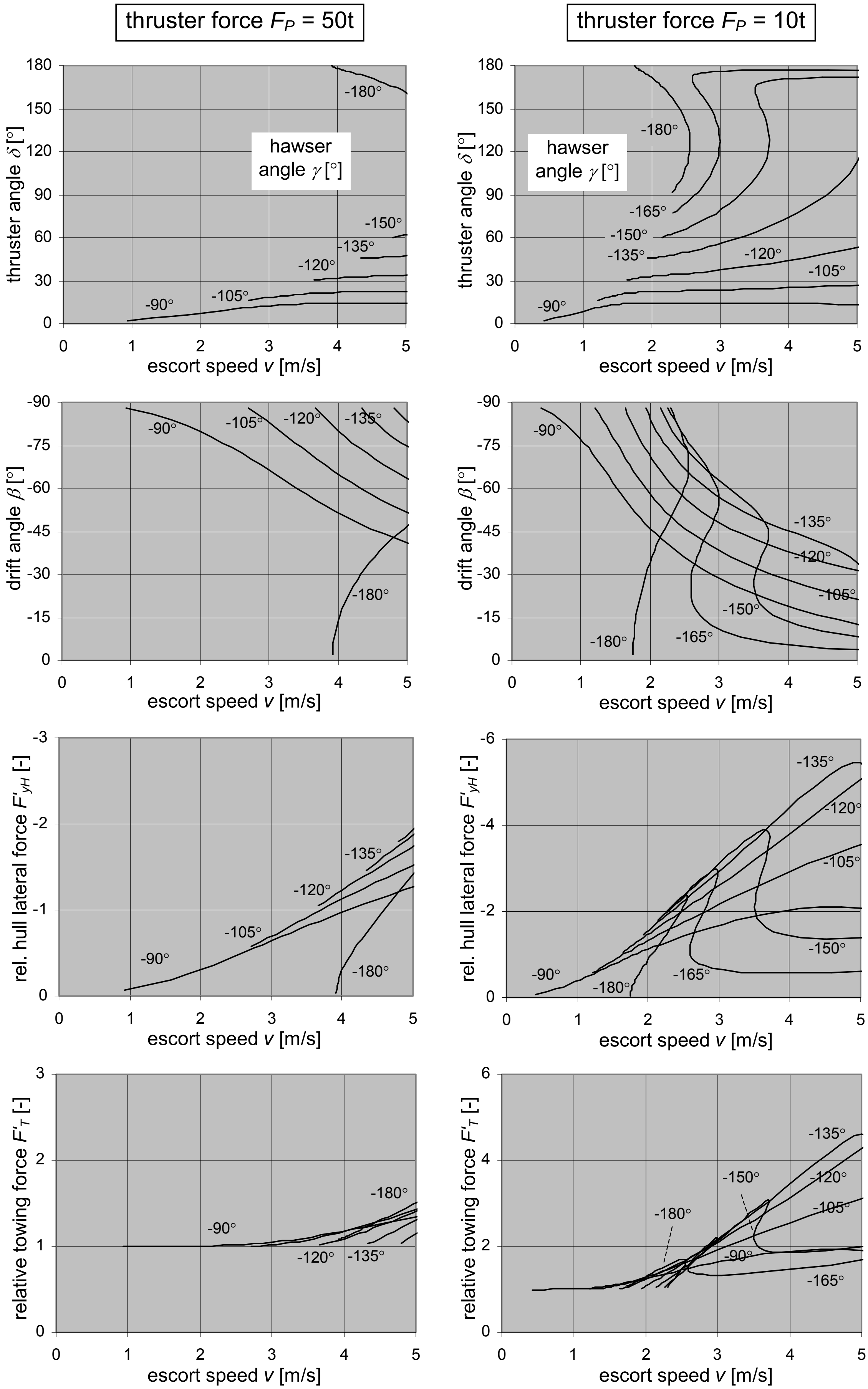

Figure 2. Kinematic and dynamic parameters of indirect (pull) towing versus escort speed

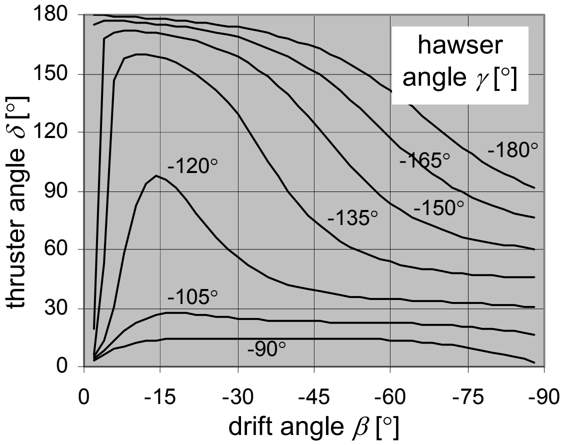

Figure 3. The drift-thruster angle relationship (as independent of escort speed and thruster force)

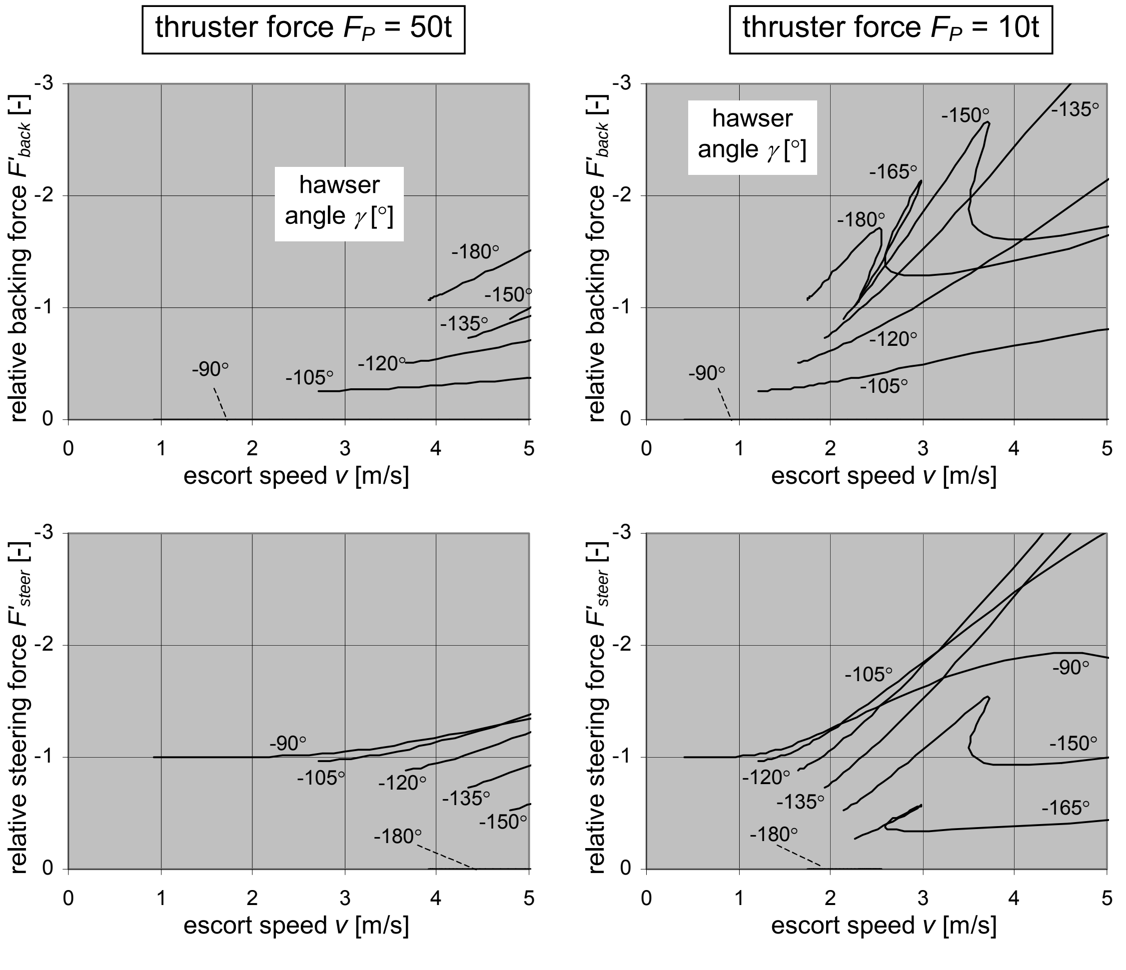

Figure 4. Distribution of the relative towing force to backing and steering components

The parameter for all the curves in sub-charts of Figure 5 is the escort speed. The pattern of these curves seems to be more interesting, rich in information and beneficial for practical purposes than that in Figure 2. Among others, Figure 5 is dived into columns according to the hawser angle, which constitutes a direct order from a pilot.

Both Figures 2 and 5 can predict the control parameters of a tug for given escort speed and hawser direction. However, a consequence in terms of the absolute tension of the hawser (towing force in tonnes) is not easily seen. Namely, the higher thruster force is accompanied with lower relative towing force, while the lower thruster force is in contrast associated with higher indirect towing effectiveness.

One might wonder whether absolute towing forces for high and low thruster forces are close to each other. The plots of Figure 2 and 5 are thus supplemented in Figure 6 with absolute values of the towing force.

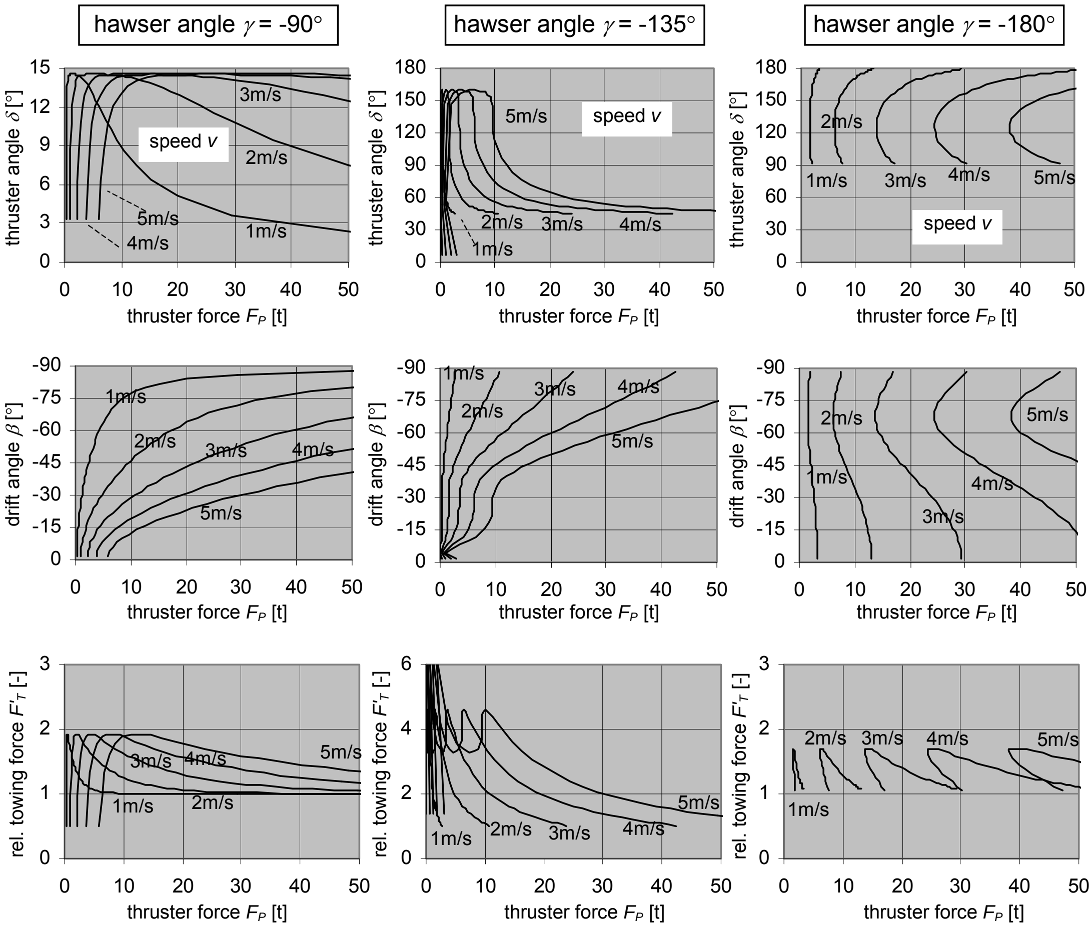

Figure 5. Parameters of tug's equilibrium versus thruster force

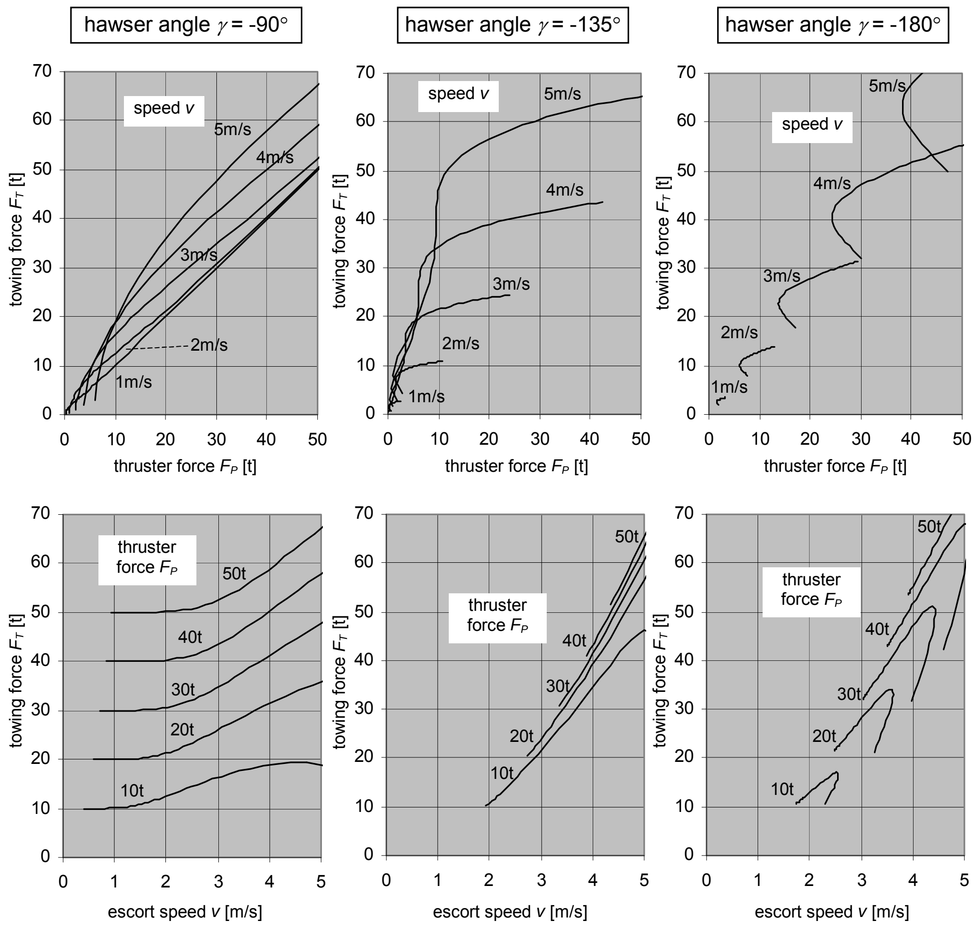

Figure 6. Absolute towing force (in tonnes) versus thruster force or escort speed.

Relative (vs. the thruster force) and absolute towing forces both have their own individual merits. The absolute force is anyhow more practical and directly ordered by a pilot. It also leads to a tug's capability in terms of the maximum effective pull under given speed, if the maximum thruster force developed for such speed is input to the computational algorithm.

The simple tug hull hydrodynamics adopted in the present paper in terms of shape and size of the hull nondimensional hydrodynamic coefficients, refer to Equation (3), implies the following features, which can be drawn from Figure 6:

– in pure steering ($\gamma = -90°$) and pure backing ($\gamma = -180°$) we are receiving the global indirect towing effectiveness of approx. 50%, i.e. the thruster force is transformed to about 50% higher values in the hawser, see the upper diagrams of Figure 6,
– in case of $\gamma = -135°$ the effectiveness is varying between zero and even several hundred percent dependent on the thruster force (the lower the better) and escort speed (the higher the better); the lower diagram for this hawser angle (showing the towing force versus escort speed) indicates the towing force during the equilibrium of a tug be almost independent of the thruster force and be influenced by the escort speed only.

The raised above points shall be validated in the future for actual hydrodynamic characteristics of tug hulls.

5 EQUIVALENCE TO PUSHING OPERATION WITH FRICTION EFFECT OR MOORING ROPE SUPPORT

The model and results having been described so far are also valid if we either consider the push operation with the friction effect between a ship's and a tug's hull or if the push action of a tug is supported by a longitudinal (with reference to the ship) mooring rope. As mentioned before, these effects were not included in [Artyszuk, 2013a]. In Figure 7 only the mooring rope case is considered, exactly consisting of a bow line. However, the friction force can be modelled in the same way, it will also point up, identically to F_M in Figure 7, since in both the situations a tug has a tendency to move towards the stern of a ship and decelerate the ship. An additional useful simplification, though quite reasonable, would be if we assume the pushing point on a tug to coincide with its mooring fairlead.

The opposite but rather theoretical direction of the longitudinal force due to mooring of friction is also possible in that a spring line is implemented instead. Anyhow, such specific case is dealing with the equivalent hawser direction angle $\gamma \in \left(-90°, 0°\right\rangle$, which is not examined in the present paper. Under such conditions, as well as in other not discussed situations, a necessity of independent operation of both thrusters might occur to achieve a tug's steady-state movement. This brings an arbitrary combination of the balancing force and the moment excited by thrusters., while the coupled/parallel mode of operation, widely used in the paper, limits (or 'stiffens') the moment to the product of the resulting lateral force and the longitudinal location of both thrusters.

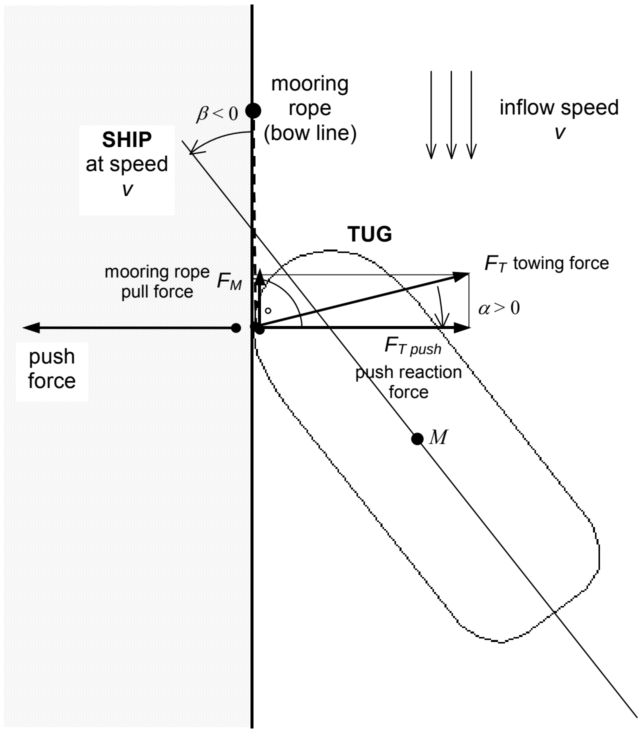

Figure 7. Equivalent pushing operation supported with a bow line

Using the numerical results of the previous chapter for the mentioned case of a pushing tug with bow line requires the following substitutions or conversions (check Figure 7 for meaning of symbols):

$$\gamma = -\left(90° + \alpha\right) \;\Rightarrow\; \alpha = \gamma - 90° \tag{19}$$

$$F_T = \sqrt{F_{Tpush}^2 + F_M^2} \Rightarrow$$

$$F_M = F_T \cdot \cos\alpha\,,\;\; F_{T\,push} = F_T \cdot \sin\alpha \tag{20}$$

In case of friction, the force F_M in Figure 7 will depict the friction force, while $F_{T\,push}$ will constitute the normal reaction, as essential in computation of the former one. The angle α represents thus the friction angle, and its tangent denotes the standard friction coefficient. Of course, the magnitude of friction-related force F_M is a small, fixed proportion of the other component $F_{T\,push}$. However, in the bow line case there is no practical limit for F_M.

6 CONCLUSIONS

The present study has revealed that both modes of towing assistance at speed: pulling and pushing operations are of the same physics and mathematical model. Moreover, the pushing model is just a portion of the most general pulling model in that it derives from the latter, refer particularly to Figure 6 and the left diagrams pertaining to case ($\gamma = -90°$). However, the term 'indirect towing' is usually applied to pulling operation only. So, in situations when tug's.hull hydrodynamic force is taken to advantage while developing a towing force, the latter being much in excess of the propeller force, either in pulling or pushing, the expression 'indirect assistance' is equally authorised according to its literal, primary meaning. This involves of course a certain drift angle of tug's hull, but its role is much more than purely preserving appropriate kinematic following of the assisted ship. Such commitment relating to the proposed wider use of the word 'indirect' took also place in the previous work [Artyszuk, 2013a], but now has been additionally proved.

The presented algorithm is flexible enough to accommodate any pattern of tug's hull hydrodynamic coefficients, and thus may result in the actual tug behaviour. The only item suffering some deficiencies is the applied simple thruster (propeller) model, i.a. not including the advance speed detrimental effect. It is believed however that the results of the present report will still be valid to some extent, since the constant values of the thruster force used in our computations shall be considered as the effective thrust force, i.e. requiring higher rpm/pitch settings if strong speed effects exist. The other phenomenon worth a future concern is also the transverse force on the propeller due to local drift angle, as contributing to the total force and thus altering the effective thrust direction. The latter can be quite different than the propeller axis.

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