Escort Tug's Stability Estimation at Design Phase

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ABSTRACT

This paper contains research results pertinent to one of the aspects of escort tug design, namely, transverse stability during steering of large ships escorted. The aim of the research was determination of the maximum heeling moment on the stage of tug design with reliability sufficient for engineering applications. Mathematical simulation of escorting a ship by a tug was used for assessing. To validate the results obtained, full-scale trials of the tug were carried out as part of the research work with a stability analysis performed for the tug model.

Keywords: *escort tug, steering, stability*

1. INTRODUCTION

During the last decade, the attention of many national and international bodies engaged in navigation safety insurance from the point of view of marine environment pollution prevention has been concentrated on ensuring the safe navigation of oil and chemical tankers in confined and shallow waters and in close proximity of the coastline.

In view of the fact the escorting of tankers not very manoeuvrable at low speeds is an efficient way to avoid grave consequences of grounding or collision as a result of a sudden loss of steerability, it has been made obligatory in some marine regions of the world, for instance, Sullom Voe in the Shetland Islands, at Southampton and Millford Haven in the UK, at Mongstad in Norway and other countries. For some regions of the Baltic Sea with heavy traffic there are also recommendations from HELCOM (2004) to members of the Helsinki Convention to apply the escorting of chemical carriers and oil tankers when manoeuvring in way of the terminals.

Since conventional harbor tugs do not ensure efficient escorting due to their parameters including sufficient stability, there has been a clear tendency in the marine design towards specialized tugs for large ship escorting (Gale and Lindborg, 1993).

Escort towing is an emergency sea operation during which the accompanying tug makes it possible to avoid grave consequences in case of engine or steering gear breakdown in the tanker being accompanied. Since the tanker crew have almost no time to avoid an accident themselves when moving in confined waters and on a current, the accompanying (escorting) tug follows tethered behind the tanker without interfering with its passage so as to be able to act immediately to the requests from the tanker in case of an emergency.

Generally, the hydrodynamic forces weaken at the rudders of most large ships in low speeds, so that the available steering force of such ships is substantially reduced at speeds below 4 ÷ 6 knots. To preserve sufficient manoeuvrability they have to maintain a speed of at least 6 knots even in tricky channel bends and narrows. On the other hand, for a tanker, the most economic speed is the highest speed permitted in the specific area or, where there are no speed limits, the highest speed at which safe passage is ensured, which is often means a speed of 10 ÷ 12 knots. As a result of this, the required escort speed is also to be at least 10 knots or even higher in some cases.

It is clear from above that escort towing is not to be referred to ship-handling operations of the usual type when speed is below 4 knots. Besides, an escort tug should not only run at the required speed, but also, if need be, to safely and efficiently brake and steer large vessels.

2. APPLICATION OF ESCORT TUGS

Tugs intended for escorting may also be engaged in dynamic assist operations with an equal degree of efficiency. The only difference between escort towing and ship assist is the fact that dynamic ship assist is not an emergency operation, and the tug function is only to improve the ship manoeuvrability.

During the escort towing, the task of the tug is to brake or steer the accompanied ship in order to avoid collision, grounding or other dangers in case of screw-rudder system failure. When providing dynamic assist, the tug takes an active part in the manoeuvring of the assisted ship. Dynamic assist is widely applied where large ships are to go through tricky channels, where currents or wind would make the passage impossible without additional steering power.

Both escort towage and dynamic ship assist is to be effected at relatively high speeds between 6 and 10 knots and sometimes even more. Therefore, the requirements for tugs intended for dynamic ship assist are the same as for escort tugs.

During escort towing and dynamic ship assistance the same “arrest modes” may be utilized. Where it is necessary to stop the tended ship or to reduce its speed without implementing any steering force, “direct arrest” is used. In the case of applying “dynamic arrest modes”, the steering and braking forces would be used simultaneously.

Direct arrest modes (both reverse and transverse arrest) utilize the tug propulsor to generate braking force. In reverse arrest, the retarding forces are generated by the thrust of propeller rotating against the water flow. This mode is applicable at speeds up to about 8 knots. At speeds above 9 knots, overloading of engine may occur where fixed-pitch propellers are used and the achieved braking force would be reduced considerably. In transverse arrest, the braking forces are produced by rotating the propeller nozzles out to an angle close to 90° from the centre line of the tug. The generated braking force is based on so-called momentum drag.

Dynamic arrest modes (indirect arrest and combined arrest) are methods applied for escort and dynamic ship assist at speeds of tended ships being 10 knots and above. In this case, the tug is steered to an angle against the direction of the water flow, and braking and steering forces are generated as a result of creation of a circuit-separation component of the hydrodynamic drug of the tug hull. These forces will grow up as the tug speed would increase.

When indirect arrest is carried out, the tug is turned into an angle of attack against the water flow by means of thrusters; typically between 30° and 60°. In this mode the azimuthing thrusters are only used to orient the tug, and the towline force is generated entirely by the hydrodynamic drug of the tug hull. The indirect mode is the most efficient method of tug operation for the purpose of turning the assisted tanker in the desirable direction or increasing the steering power during the dynamic assist of the ship.

In combination arrest mode, azimuthing thrusters are turned to angles exceeding 90° ÷ 100° and are oriented near perpendicular to the direction of water flow. Thus, the momentum drag of the water column supplements the hydrodynamic drag of the tug's hull. Despite the fact the combination arrest mode appears the most efficient one in opposing the turning of the escorted ship, it is not often used during dynamic support operations because, when it is used, highest towline tension can be generated which results in high breaking force component.

To be efficient enough, an escort or dynamic support tug is to develop a high pull without prejudice to its own safety. As may be seen from above, the dynamic arrest mode is the most dangerous from the point of view of high heeling moments being generated because, when it is applied, the towline is typically oriented athwartship or nearly so and the entire towline force is resisted by the tug's transverse righting moment. From this, one can derive that an escort tug is to possess sufficient stability to be able to effectively withstand the generated towline forces without excessive heel.

Unfortunately, no generalized methods are available today to assess the heeling moments which influence the tug during escort operations. As a result, all the known stability criteria which are applicable to escort tugs, see, for instance, Det Norske Veritas Rules (2005) use values of heeling moment derived from test.

3. MATHEMATICAL MODEL OF TUG'S MOTIONS AT ESCORTING

At present, the principal experimental method of assessing, on the design stage, the tug stability during escort operations is so-called "direct" modelling of the escorting process during which the maximum checking force, tension force in towline and maximum angle of tug heel are determined by experiment with self-propulsion model, as described, for instance, in Birmingham (2000).

As an alternative, this paper analyses the possibility of determining the heeling loads upon an escort tug by developing the theoretical equations of tug's motions at the escort for the purpose of solving of which experimental equation coefficients are used only.

For simulation the operation of a tug in the dynamic arrest mode, the case of an escorting tug which moves behind the assisted ship at a drift angle and steered the ship with the towline is adopted as the design case (Fig.1).

When determining the forces acting upon the tug, the following assumptions and simplifications are made:

- the escorted ship and the tug are moving in a straight and uniform manner and do not change the position with regard to each other;
- the heeling angles of the tug are small enough to consider the hydrodynamic forces acting upon the tug to be applied on the horizontal plane;
- the hydrodynamic interaction between the hulls and propulsors of the escorted ship and the tug is small and negligible;
- the towline is considered to be a weightless and stiff;
- the effects of wind, waves, currents and shallows are ignored.

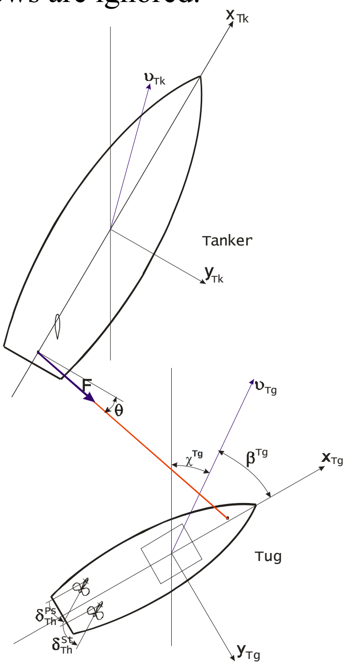

Figure 1 Escort configuration

As a result, the tug's motions on the horizontal plane may be described using the system of ordinary differential equations (1), which is similar to proposed by Waclwek & Molyneux (2000) but taking into consideration three degrees of freedom (roll motions excluded for simplicity).

$$\rho\nabla(1+k_{11})\frac{d\upsilon_x}{dt} = -\rho\nabla(1+k_{22})\upsilon_y\omega + \qquad (1)$$
$$+X_{Tg} + X_{Th}^{St} + X_{Th}^{Ps} + \delta X_{Th}^{St} + \delta X_{Th}^{Ps} + X_{tow}$$
$$\rho\nabla(1+k_{22})\frac{d\upsilon_y}{dt} = \rho\nabla(1+k_{11})\upsilon_x\omega +$$
$$+Y_{Tg} + Y_{Th}^{St} + Y_{Th}^{Ps} + \delta Y_{Th}^{St} + \delta Y_{Th}^{Ps} + Y_{tow};$$
$$J_z(1+k_{66})\frac{d\omega}{dt} = M_{Tg} + M_{Th}^{St} + M_{Th}^{Ps} +$$
$$+\delta M_{Th}^{St} + \delta M_{Th}^{Ps} + M_{tow};$$
$$\frac{d\xi}{dt} = \upsilon_x \cos\chi - \upsilon_y \sin\chi;$$
$$\frac{d\eta}{dt} = \upsilon_y \cos\chi + \upsilon_x \sin\chi;$$
$$\frac{d\chi}{dt} = \omega,$$

where

∇ - volume displacement of the tug;
J_z - yaw inertia moment of the tug;
k_{11}, k_{22}, k_{66} - added masses and added yaw inertia moment of the tug;
υ_x, υ_y - speed projections;
ω - tug rotating velocity;
χ - the course angle of the tug;
ξ, η - the tug coordinates in a semi-fixed coordinate system;
X_{Tg}, Y_{Tg}, M_{Tg} - the hydrodynamic forces acting upon the tug hull;
$X_{Th}^{St}, Y_{Th}^{Ps}, M_{Th}^{St}$ - the hydrodynamic forces and moment due to the starboard azimuthing thruster operation;
$X_{Th}^{Ps}, Y_{Th}^{Ps}, M_{Th}^{Ps}$ are the hydrodynamic forces and moment due to the port azimuthing thruster operation;
$\delta X_{Th}^{St}, \delta Y_{Th}^{Ps}, \delta M_{Th}^{St}, \delta X_{Th}^{Ps}, \delta Y_{Th}^{Ps}, \delta M_{Th}^{Ps}$ - the correction of forces and moments due to interaction between thrusters themselves and the tug's hull;
$X_{tow}, Y_{tow}, M_{tow}$ - forces and moment acting upon the tug from the towline side.

As already stated, the hydrodynamic forces included in the above expressions are determined by the results of model tests. The forces and moment acting upon the tug from the towline side are calculated using the towline end coordinates determined from the equations describing the tug and tanker mutual motions.

If need be, the suggested equations describing the tug's motions in calm water may be supplemented with equations describing the ship behavior in waves. In this case, the dynamic pulsations of towline force and the heeling moment, accordingly, will also be determined.

By using the results from the above equations for describing the motions in calm water, the heeling moment acting upon the tug in the transverse plane would be determined from the moment equation with regard to the base plane of the tug, by the formula (2):

$$M_h = Y_{tow} z_{tow} + (Y_{Th}^{Ps} + Y_{Th}^{St}) z_{Th} - Y_{Tg} z_{Tg}, \qquad (2)$$

where

z_{tow}, z_{Th}, z_{Tg} are the height of towline staple above the base plane on the centreline plane of the tug, height of azimuthing thruster propeller axes above the base plane and height of the total hydrodynamic force, accordingly.

4. MODEL TEST DETERMINATION OF THE TUG'S HYDRODYNAMIC CHARACTERISTICS

For the experiment, an escort tug built in 2005 was chosen, which has the principal hull dimensions shown below:

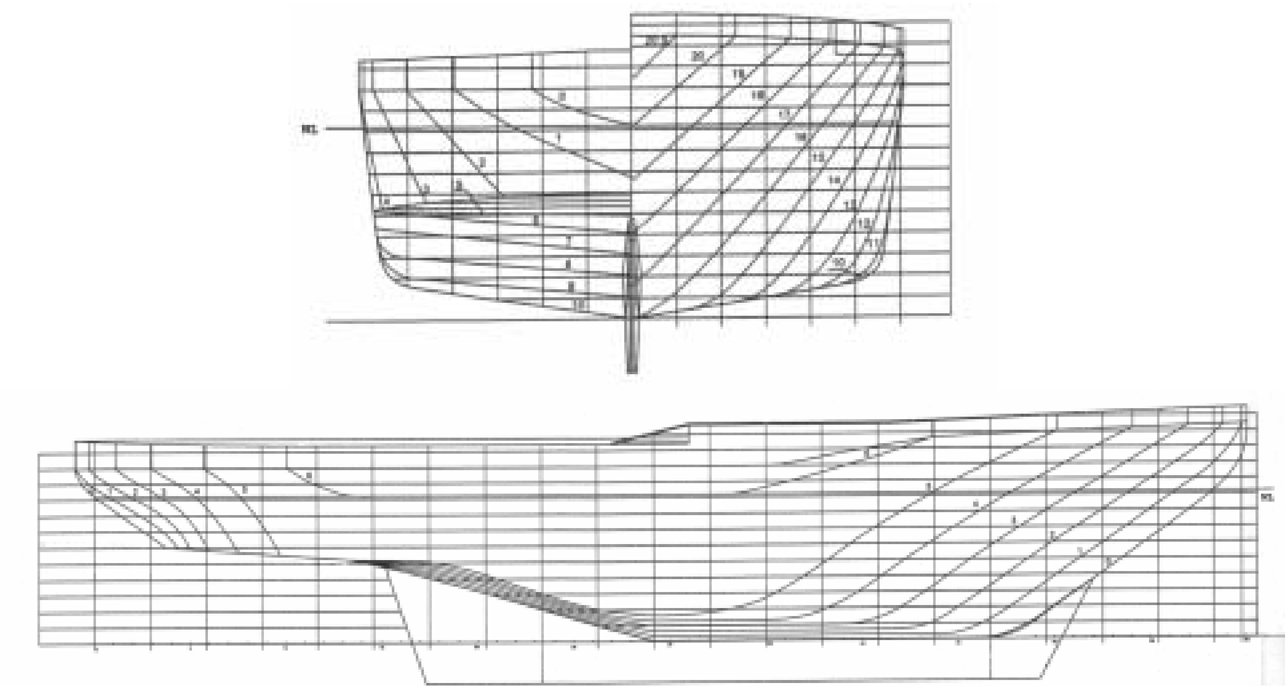

Figure 2 Lines drawing of hull of the escort tug examined

The lines drawing of hull is to be found in Fig. 2.

Length on waterline, m	35.0
Breadth on waterline, m	12.60
Depth amidships, m	6.20
Draught, in m	4.60
Displacement, m^3	952.0
Block coefficient	0.469

The hydrodynamic characteristics of the tug necessary to solve the mathematical model of its motions were determined by experiment in rotating arm tank with a model manufactured to the scale 1:30.

The test program included the following:

- testing the tug model without thrusters to determine the hydrodynamic characteristics of a bare hull in dependence on drift angle;
- testing the tug model with a single azimuthing thruster to obtain data for determining the forces generated during the thruster operation at arbitrary rates of their rotation numbers and angles (the interaction of the thrusters being disregarded);
- testing to determine the interaction of the thrusters.

During the above tests, the captured model was towed at drift angle β^{Tg} which varied from 0º to 180°. When determining the forces due to the azimuthing thruster operation, the propeller speed was measured from 0 to the maximum value at which the thruster pull in the mooring mode, when converted to full-scale values, would correspond to the design data.

By way of illustration, the dimensionless hydrodynamic forces arising on the tug hull (no azimuthing thrusters) are shown in Figs. 3 ÷ 5, where:

C_y – lateral force coefficient,

C_m – yaw moment coefficient,

C_{mx} – heeling moment coefficient due to lateral hydrodynamic force application.

In Fig. 6 the elevation of the application point of lateral hydrodynamic force is shown with regard to base plane, as percentage of the tug draught.

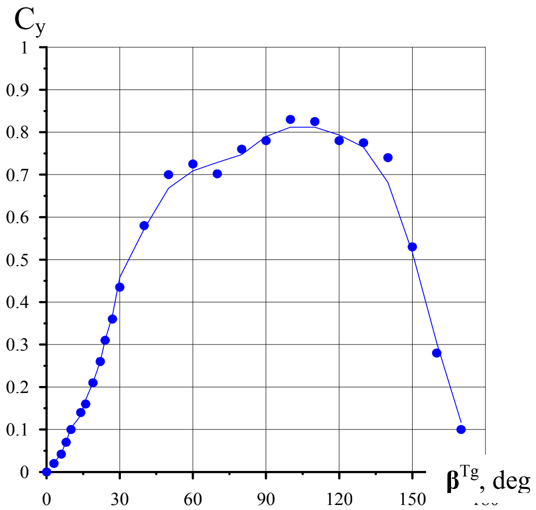

Figure 3 Lateral force coefficient versus the tug's drift angle

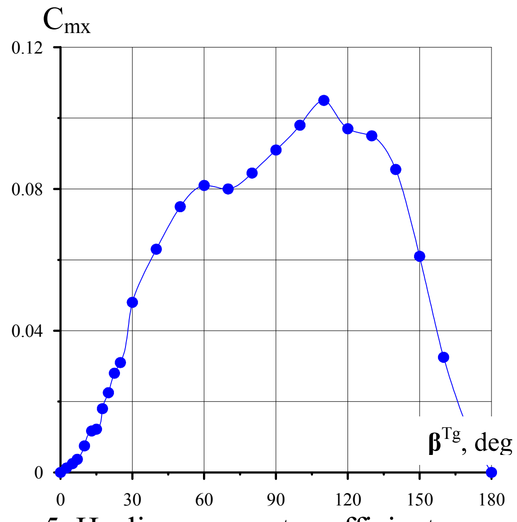

Figure 5 Heeling moment coefficient generated by lateral hydrodynamic force versus the tug's drift angle

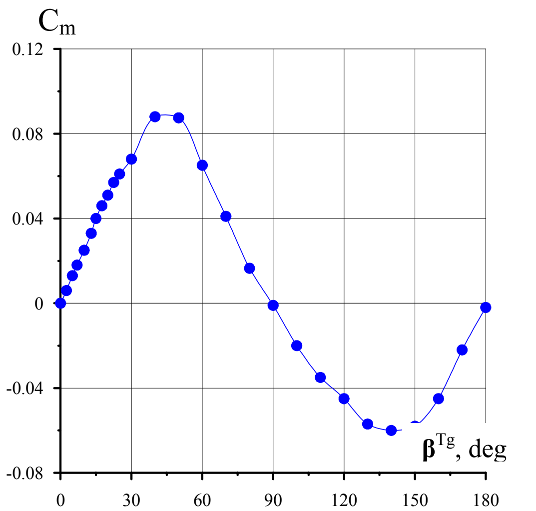

Figure 4 Yaw moment coefficient versus the tug's drift angle

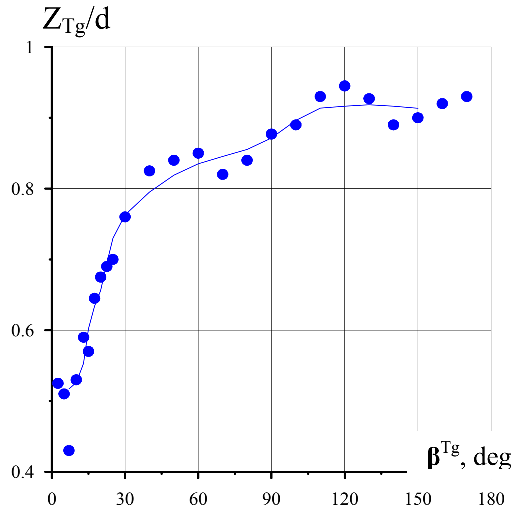

Figure 6 Non-dimensional height of the application point of lateral hydrodynamic force versus the tug's drift angle

5. MATHEMATICAL MODELLING OF TUG'S MOTIONS IN ESCORT MODE

Modelling of tug's motions in escort mode was carried out using the mathematical model developed.

The towing staple was located in CL 14.7m forward of the tug's midship section; the elevation of azimuthing thruster axes above the base plane was 0.7m. The calculations were performed for escorted tanker speeds of 6.9 and 9.8 knots. The following was determined from calculations for the specified speeds: towline force value, its projection on the coordinate axis of the tug and escorted tanker, tug drift angle, angle of deviation of towline from tanker CL, data on hydrodynamic forces at all possible combinations of port and starboard azimuthing thruster angles, and, as a result, the values of the heeling moment acting on the tug during escorting operations.

As a calculation example, Fig. 7 shows the diagram of steady-state heeling moment as a function of the drift angle at escorting speeds of 6.9 and 9.8 knots (the data correspond to the tug loading at full-scale trials). The calculated escort parameters corresponded to the above speeds are presented in Tab. 1.

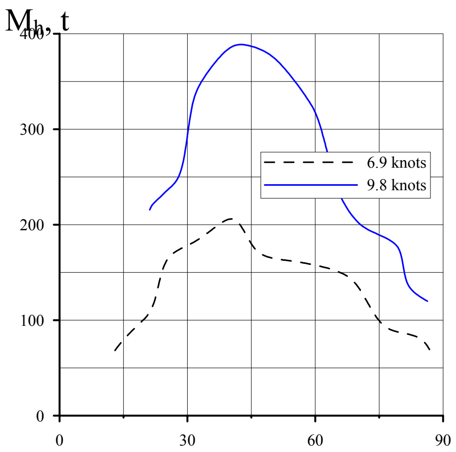

Figure 7 Escort heeling moment versus tug's drift angle

Table 1 Calculated escort parameters.

Escorting speed υ_{Tg}, knots	6.9	9.8
Tug drift angle β^{Tg}, deg	40.8	41.5
Angle between tow line and tanker's CL (90^o-θ), deg	42.1	34.0
Towline force F_{tow}, t	63.6	99.2
Maximum steady moment M_h, t	205.8	388.2

6. FULL-SCALE TRIALS TO ASSESS TUG'S ESCORT CHARACTERISTICS

The trials were carried out in June 2005 in the Gulf of Finland, with sea state 1 and wind of 1.8 ÷2.5 m/s. The tug was loaded about 50% of full loading. The tanker "Seabravery", 244m in length and displacement of 123,000 t, was used as escorted vessel.

During the escort mode trials the tanker was maintaining a steady course by means of the automatic pilot, which compensated the tug's steering force. By putting the tug's azimuthing thrusters over and simultaneously increasing the propellers thrust, the tug was made to take a position corresponding to the maximum steering force. The tug's winch was fixed.

The main escorting parameters measured at towing speeds of about 7 and 10 knots are presented in Tab. 2.

Table 2 Escort parameters measured at full-scale trials.

Escorting speed υ_{Tg}, knots	6.9	9.8
Tug drift angle β^{Tg}, deg	33.5	34.7
Angle between tow line and tanker's CL (90^o-θ), deg	38.2	52.0
Towline force F_{tow}, t	66.3	90.7
Tug steady-state angle of heel/tug dynamic angle of heel φ_{st}/ φ_d, deg	5.0/6.4	10.5/12.1

To determine the maximum steady-state heeling moment acting on the tug during tanker escorting, a righting lever curve for 50% loading was plotted (Fig. 8), whose intersection with the heeling moment arm determined the equilibrium heeling angle at towing.

The heeling moment corresponding to the static angles of heel of 5º and 10.5º as recorded at the trials, are defined by the following equalities:

$$M_h^{6.9kn} = \Delta_{Tg} \cdot ZG_{5^\circ} = 940t \cdot 0.21m = 197.4t\ .$$

$$M_h^{9.8kn} = \Delta_{Tg} \cdot ZG_{10.5^\circ} = 940t \cdot 0.445m = 418.3t$$

A comparison of measured data grouped into Tab.2 with the results of mathematical modelling placed in Tab.1 of the preceding section shows that the relative divergence between the design and the full-scale test estimates of the steady-state heeling moment and, consequently, the static angle of heel of the tug is equal to (4 ÷ 7)% at approximately the same mode of escorting.

In contrary to the above indicated small discrepancy between the calculated and measured static angles of the tug, there is a rather noticeable difference of the drift angles and, as a result, difference of angles between tow line and tanker obtained during the sea trial and the mathematical simulation when the escort speed is about 10 knots.

There are two possible reasons of the above. The first one is ignoring of heeling angle occurred during the dynamic arrest mode, which exceeds 10 deg at the escort speed of 10 knots. As a result, this can produce affect on tug's hydrodynamic coefficient values. The second one, which led to different results of the trials and the simulation, is a total methodological error of the rather complicated model experiment involved.

As regards the dynamic heeling moment characterized by the angle of heel φ_d, the last table shows that its effect on the tug results in a heel increase of about 20%. However, it should bear in mind here that, since the behavior of an actual tug is largely influenced by the actions of the tug master and can significantly affect the dynamic heel, the value φ_d seems to be able to vary within a wide range.

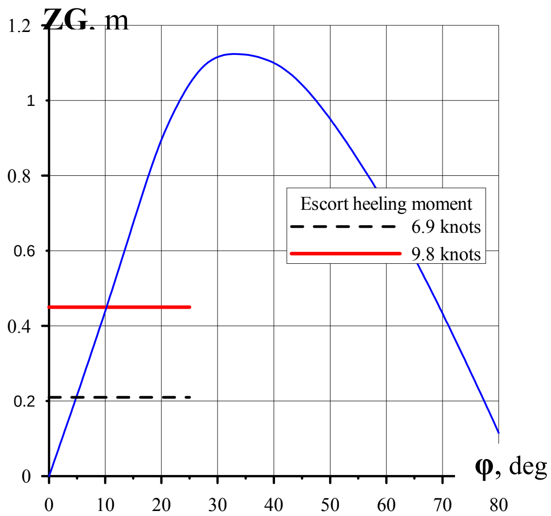

Figure 8 Righting lever curve of the escort tug at the full-scale trials.

7. ANALYSIS OF RESULTS AND CONCLUSIONS

Being quite aware of the complexity of a dynamic system such as a tanker and an escort tug connected to each other by an elastic line and interacting with each other, we have, in this paper, made an attempt to simplify the system mathematical model as far as possible, taking account of its main defining static and dynamic characteristics only.

As a result, the simplified mathematical model defining the motions of a tug engaged in an escorting operation, as set out in the paper, has been able to fairly adequately reflect, from a practical standpoint, the main static and dynamic properties of the tug in escort mode.

We believe that this was possible, in contrast to many of the "early" mathematical models, due to considering, when formulating motion equations, both the forces arising from hydrodynamic interaction of the thruster and ship hull and the thruster – thruster interaction, and the position of the sum vector of hydrodynamic forces on the hull in the depth direction as a function of the tug drift angle. The key factor in solving motion equations has naturally been the use of equation coefficients experimentally determined at tug model tests in a rotating-arm tank.

Since, in contrast to "direct" model tests, the use of an experimental-and-design mathematical model makes it possible to model any tug escort scenarios, we believe that the proposed tug's mathematical model, if supplemented by tanker movement equations, may be used to develop training simulators modelling the control of both vessels when navigating through narrow and tricky channels.

The above conclusions are also supported by the good similarity of data on escort tug's stability qualities at full-scale trials where the tug under consideration is engaged in escorting operations in natural conditions, to simulated ones at the design phase of the escort tug manufacture.

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