Carrousel Tug Design

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SYNOPSIS: Nowadays tug design can be characterized by keeping the hull direction in line with the towing wire and rotating the thrust force 360-degree around. The new carrousel tug design can be characterized by rotating the hull direction free from the towing wire. This carrousel consists of a large horizontal ring, rotating around the accommodation and fitted with the towing wire. The attachment in the side reduces the heeling moment sharply and enables to use the full extent of the dynamic hull forces for escorting (steering and braking) to be used.

Fig. 1 Scale model of the carrousel on a conventional Combi tug

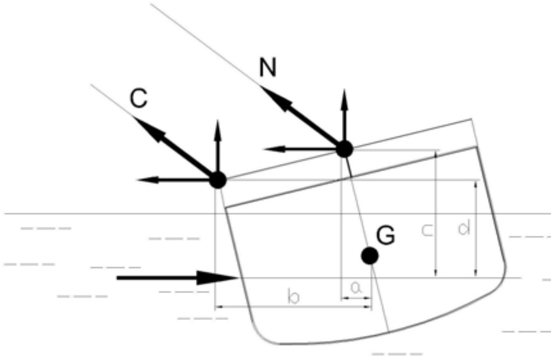

Fig. 2 The effect of a radial support (C) and normal attachment (N)

1. Introduction

1.1 Present design focus on propulsion

The past 20 - 25 years design of harbor tugs has concentrated on developing and improving the propulsion and the associated maneuverability. Propulsion moved from single to double prop, various nozzles and rudder types were introduced and finally the propulsion developed into omnidirectional thrust by two or more thrusters [1], [2] or VSP [3]. This development forms the base of the present day tendency of fully omnidirectional propulsion with ever increasing bollard pull and with to a lesser extent use of hydrodynamic forces by skegs and/or box keels [4] and [5].

1.2 Little focus on towing wire attachment

In contrast to the extensive developments in tug propulsion, relative little developments were seen in the towing wire attachment to the ship's hull. Already dating back to the fifties, many tow hooks were based on some kind of radial support (e.g. 'Seebeck patent') using a half circular vertical guiding support of the towing hook to move the attachment point towards the side and thereby reduce the heeling arm, see fig. 2. Radial supports have also been used to support fairleads instead of towing hooks. For further recent developments on radial support, see e.g. [6].

For conventional tugs, this support was placed near the center of lateral resistance (CLR). With the newer tug and propulsion types appearing, the towing point was moved away from the CLR towards bow or stern to ensure that an 'overload' in the towing wire would lead to a rapid turn of the hull axis in line with the force and thereby prevent capsizing. This feature in combination with wide-bodied hulls offers a fairly good protection against capsizing instead of the radial support and is widely applied on modern ASD and tractor tugs.

1.3 New towing wire attachment: The carrousel

This paper describes a new revolutionary patented approach to connect the towing wire to the ship's hull with a full circular ring, the so-called carrousel. This carrousel offers three important features:

1) All around flexibility

The carrousel ring can rotate freely all around without limitations and towing operations can be freely changed from bow to stern use or vice versa, see fig. 3.

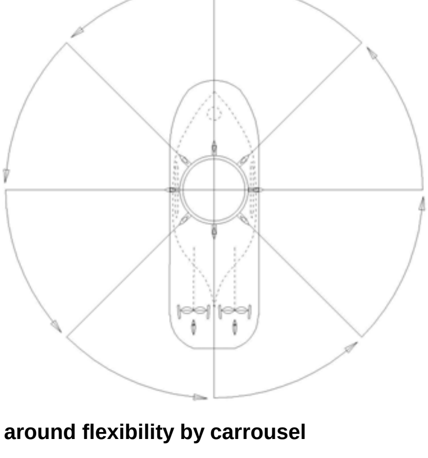

Fig. 3 All around flexibility by carrousel

2) Large stability enables to increase hydrodynamic forces
The carrousel is based on the same principle as a radial hook, but now extended to the full ship's width. Hereby a large increase in stability is achieved, which can be used to increase the hydrodynamic forces.

3) Towing wire attachment point near lateral centre
The stability feature enables to position the carrousel right above the center of the lateral resistance and thereby maximize the towline forces and minimize the need for steering propulsion on the tug.

The carrousel is independent of the propulsion type and can therefore be applied to any type of tug design and propulsion type (and to a wide variety of smaller sized workboats). However, in this phase already special attention is drawn to the attractive combination of the carrousel with conventional shaft propulsors. This combination raises the performance of 'conventional' tugs to a significant higher level, leaving many of the clear drawbacks of these tug types behind.

The carrousel is still in an ongoing development and practical experience will finally determine the overall performance and use as stern and/or bow tug(s). Therefore in this phase, all comments and criticism are welcome to assist the development, the application of the carrousel and to improve the design in a joined effort. Special attention is also drawn to the safe operational deck procedures for the freely rotating winch for both stern and bow area.

One topic of further development is the design of a compact winch on the rotating carrousel.

2. Development of the concept

2.1 Background

During the on-going development of various new tug concepts, the carrousel itself formed a clear and important step forward and is therefore considered in detail in this paper.

2.1.1 Design study: Thrust Liner (TL)

In 1997, IMC started a preliminary design study for future tug development in the Port of Rotterdam, with a clear focus on harbour assistance: Low towing speeds, large bollard pull and little hydrodynamic lift / drag forces.

The most logical solution for this setting is based on a force vector diagram : ***Keep the Thrust vector all around in line with the towing Line.*** This solution could be achieved by one thruster located below a freely rotating winch around the accommodation.

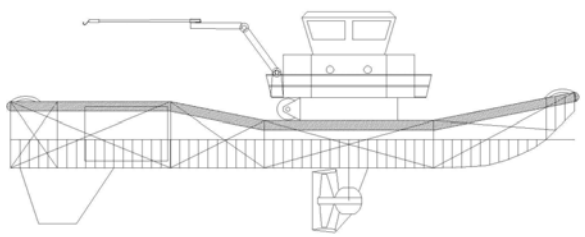

Fig. 4: Thrust Liner in side view

2.1.2 Design study: Thrust Lift Liner (TLL)

The Thrust Liner was purely based on bollard pull and low speed assistance. For higher speed assistance the use of hydrodynamic forces was investigated by large skegs below the carrousel, leading to the following logical solution: ***Keep the Thrust all around and the hydrodynamic Lift forces in transverse direction in line with the towing Line***

This solution could be achieved by a double skeg arrangement below the carrousel and a twin thruster arrangement: One thruster in the bow (SB) and one mirrored aft (PS). By this arrangement, the center of the thrust remains all around below the carrousel and the heading of the hull can be controlled.

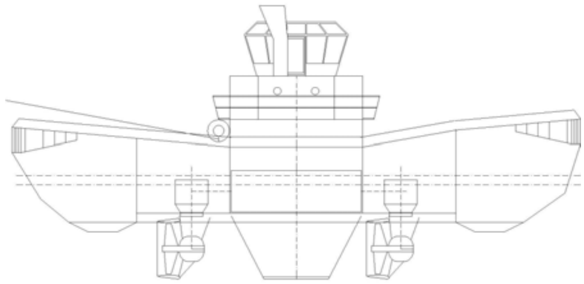

Fig. 5 Thrust Lift Liner in side view

2.1.3 Design study: Carrousel on conventional tug

Although the effectiveness of the TLL was without any doubt, the necessity of thrusters was discussed and the associated increase in draught (similar as for tractor tugs). Further developments lead to the focus on longitudinal shaft propulsion and transverse hydrodynamic forces, with the following solution. ***Keep the thrust longitudinal and the hydrodynamic lift forces transverse in line with the towing line.*** This solution could be achieved by a double skeg arrangement below the carrousel and conventional single/twin propulsion aft, possibly assisted by a small (retractable) thruster in the bow.

The design options are summarized in table 1 below:

Carrousel development	THRUST below towline	LIFT below towline
Thrust Liner (TL)	Centered 360 degree around	-
Thrust Lift Liner (TLL)	Centered 360 degree around	Centered transverse only
Conventional Carrousel Tug	Centered longitudinal only	Centered transverse only

Table 1 : Carrousel development

2.2 Functioning

The carrousel offers three new functional aspects:

2.2.1 All around flexibility

Traditionally tug design concentrated on towing over the stern behind the accommodation offering a free range of slightly more than 180 degrees for the towing wire. However, for many jobs more freedom is required and therefore the hull is turned 180 degrees. Modern ASD tugs use the same principle and rotate the whole hull and towing wire around the thrusters.

However, the thought of easily changing towing over stern to bow or vice-versa, has always been an ideal for tug operators.

Further, since the towline attachment point coincides with the CLR, changes in towline loads do no longer turn the tug's hull direction. This enables to control the hull and sailing direction properly and offers a whole range of new opportunities in assistance.

Two typical examples, one for aft tug, second for bow tug, see fig. 18 and 19:

I) Aft tug sails bow first with towing wire over bow (A):
- a) To brake the ship at higher speeds, the tug's hull is turned rectangular to the flow using the maximum hydrodynamic drag forces (wire over side) (B).
- b) To steer/pull the ship, the tug sails along outer circle forward and starts pulling the ship, (wire over stern) (E).

II) Bow tug sails bow first with towing wire over stern (I):
- c) To brake the ship at higher speeds, the tug sails along outer circle aft and the hull is turned rectangular to the flow, dragging alongside the ship (wire over bow/side) (L).
- d) To brake the ship at lower speeds, the tug reverses and sails backward braking with full bollard pull ahead (wire over stern).

2.2.2 Large stability enables to increase hydrodynamic forces (lift & drag)

The large effect of the wide radial support for a typical carrousel tug design is shown in the following graph, (see fig. 6).

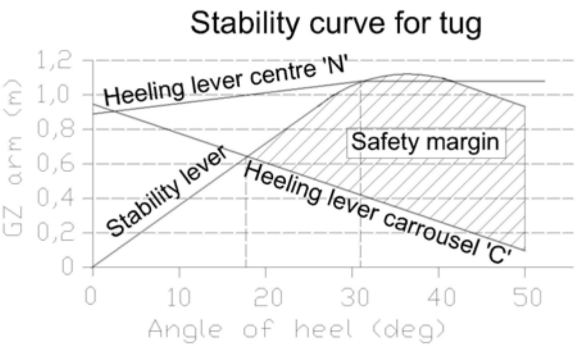

Fig. 6 Graph of Heeling leverarm for Normal and Carrousel, Righting leverarm and hatched safety margin carrousel

For a normal tow line attachment near the ship's center, the heeling lever shows a slight increase, for the carrousel however, the heeling lever lowers rapidly downwards and reaches 0 (!) nearby 50 degrees.

For the maximum towline load, the static equilibrium for the Normal heeling leverarm (N) is 31 degrees, for the Carrousel heeling arm (C) the angle is reduced to only 18 degrees. Far more important for the safety of the tug is, of course, the stability range, which shows a generous safety margin for the carrousel, see also Area Ratio concept [7].

Analyzing the above stability curve, the conclusion is clear and simple: **Capsizing due to towline force is statically no longer possible for the carrousel tug !!!**

The dynamic towline aspects are described in chapter 4 on model testing and show no danger for capsizing due to dynamic towline forces. However, other external forces may still lead to capsizing of the tug !

What are then the practical implications? In order to take advantage of this large radial support of the carrousel, the tug must heel to a certain degree (typical 10–15 degrees) to counter the large towing forces. Therefore, already in the design stage, due consideration of these angles on the functioning of the machinery and crew must be included.

The traditional danger of '**deck immersion as last warning before capsizing**', is technically no longer present for a carrousel tug, although psychological still present!

Even a substantial amount of water on deck, leaves still sufficient stability safety margin to ensure proper towing operations. Also operations in exposed port areas with significant wave heights can be performed safely.

What is then the final limitation to towline force? Primarily the strength of the towing gear itself (including dynamic peak values) and the buoyancy of the tug's hull. Instead of the traditional heeling angle limitation, the master requires the practical use of a towline load tensioning meter and a clear sight on the water flow over deck.

2.2.3 Towing wire attachment point near lateral center

In modern escort tugs the attachment point of the towing wire is located substantially before the lateral center (in indirect mode) primarily for stability reasons in case of overloading.

In the carrousel tug, the stability issue is solved by the large radial support. Therefore the attachment point of the towing wire can be positioned right above the center of lateral resistance, producing the highest tow-line forces : Ratio towline force / hydrodynamic force ≈ 1 (higher than values mentioned in [6] for **Towliner** 0.78 and Tractor tug 0.63).

The force diagram for the carrousel tug is shown in fig. 7.

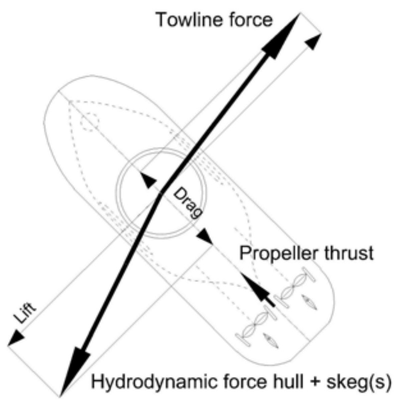

Fig. 7 Force balance for carrousel tug in indirect mode

2.3 Advantages of new carrousel

2.3.1 Cost

Building cost

Compared to a modern omnidirectional propulsion system for tugs, the conventional shaft system with FPP or CPP offers a substantial reduction in cost. Further, the efficiency of shaft propulsion with large diameter propellers is higher (typically 15 – 35 %), see table 2. This advantage can be either used to achieve a higher bollard pull, or to install smaller main engines.

Name	no. eng	kW	Pull (ton)	kgf kW	/ in %
VSP *Ajax* [3]	2	3460	90	13	61%
ASD *Thorax* [5]	2	2646	90	17	80%
ASD *Smit Mississippi* [8]	2	1830	61.3	17	79%
RT Magic [2]	3	1566	75	16	75%
Zeus [9]	2	2709	101	19	88%
Multratug 12	3	331	21	21	100%
Carrousel Tug	2	2025	86	21	100%

Table 2 : Propulsion efficiency

The relative low additional cost of the carrousel with standard rollers does still favor the total building cost of the carrousel tug and offers a reduction in range of 15 – 25 % compared to omnidirectional propulsors.

Operational cost
The use of hydrodynamic forces instead of / in addition to propulsion power offers a sharp reduction in operational cost due to lower fuel consumption and shorter running hours. This also result in less environmental pollution. Further the proven conventional shaft technology results in lower maintenance cost. And finally, the carrousel is based on sealed roller bearings with long maintenance intervals.

Note: most significant reduction in fuel cost is achieved, when a stern carrousel tug brakes the ship by hydrodynamic dragging sideward 90 degrees to the flow, nearly without propulsion power (fig. 18, cond. B)

2.3.2 Effectiveness
All around flexibility
The carrousel can be used both as bow and stern tug and offers easy and flexible operation plus additional safety to control the hull direction independent of the external tow force.

Large hydrodynamic forces
The large assistance forces for steering and braking increasing with ship's speed and can be used effectively to assist a ship at higher sailing speeds.

2.3.3 Safety
The risk of capsizing due to towline forces is minimized and the tug can be safely used in exposed areas with waves.

The large safety margin offers additional potential to counter a possible 'accident'.

3. Preliminary design of carrousel

3.1 Introduction

The design of the carrousel forms a close interaction with the tug design, the chosen beam (at deck level), the position in length in relation to the CLR, the position in height in relation to the stability range and the general arrangement.

Based on the tug interaction, the optimal structural design for the carrousel shall be investigated leading to the conceptual design presented in this paper. Finally, operational considerations are discussed.

3.2 Interaction with tug design

3.2.1 Diameter
The diameter of the carrousel is chosen nearby the beam of the vessel for the following reasons:

- Optimization of the stability effect of the carrousel
- Maximize the deckhouse space within the carrousel

3.2.2 Position on the vessel in length in relation to the CLR
The optimal position in length shall be determined by hydrodynamic investigations (including model tests). The hull can be compared to an aeroplane foil with lift and drag components; the center of lateral resistance (CLR) varies between 1/3 and 1/2 of the length (lift/drag). Detailed investigations of the position should be made in close interaction with the hull shape and the fitting of skegs, see e.g. [3].

3.2.3 Position on the vessel in height in relation to the stability range
The optimal position in height is a clear compromise between small initial heeling arm and a large stability range. The first having a traditional low position with little freeboard and small heeling angles (e.g. 6 - 12 degrees) when towing, but as a result also small stability range and rapid water on/over deck.

The second having a rather unconventional high position with a large freeboard and large(r) heeling angles when towing (e.g. 12 - 18 degrees), but as a result a large stability range, a large excess of buoyancy and minimal water on/over deck.

For large towline force and extreme conditions various model tests have shown that the second strategy of a higher freeboard provides better results.

3.3 Structural design

During the development of the carrousel structure a large variety of concepts were considered and designed. In principle, two versions were considered:

- A strong fixed circular 'T' shaped rail, fitted with a small moving part-circle 'U'-shaped horizontal trolley (similar as used vertically for lifting equipment) equipped with a tow hook.
- A fixed inner ring with rails and a large full-circle ring with rollers all around the circle and equipped with a tow hook.

Although simplicity favored the first solution, structural optimization clearly favored the second solution.

Based on the design mission and the hydrodynamic investigation, the loads shall be determined with a horizontal and vertical component.

3.4 Conceptual design

This paper is limited to the main parameters of the design, without a detailed explanation of the design parameters.

- Stiff inner ring forming integral part of deck structure and accommodation support
- Flexing outer ring forming against stiff inner ring
- Rollers between fixed inner and rotating outer ring
- Number of rollers fitted on outer ring (fixed according to loading pattern turning with outer part)
- Structural optimization performed with the use of FEC, showing advantage hinged towing arms

3.5 Operational aspects

For the carrousel tug three parameters appear important:

3.5.1 All around rotating of carrousel

Although in principle not different from present day towing operation, safe operational deck procedures are necessary and no human action should be performed on deck during towing. During pickup of the connection and release of the towing connection, the carrousel rotation shall be **temporarily blocked** to allow safe deck operations.

3.5.2 Sailing at substantial heeling angle and water on deck

For the carrousel tug with large towline forces, these parameters can increase substantially, introducing additional risks for crew on deck. Combined with the free rotating towing wire, deck operations should be minimized under these circumstances.

3.5.3 Entering the deckhouse over the carrousel

For small sized tugs, entering the deckhouse shall be done by passing over the carrousel. For large sized tugs, a separate entrance from the lower aft deck below the carrousel can be made.

4. Design investigation carrousel on existing conventional tug

As part of the design study into the new carrousel and the fitting on new tug designs, more insight is required on the practical and operational aspects of such a new design concept. Therefore the new carrousel was first investigated on board of an existing tug design.

4.1 Choice of test tug

Various existing tug types have been considered for retrofitting a carrousel, with specific attention to maneuverability and structural integration of the carrousel. Finally the Combi tug Multratug 12 of Multraship Towage & Salvage was chosen as a good compromise (see fig. 8 and table 3).

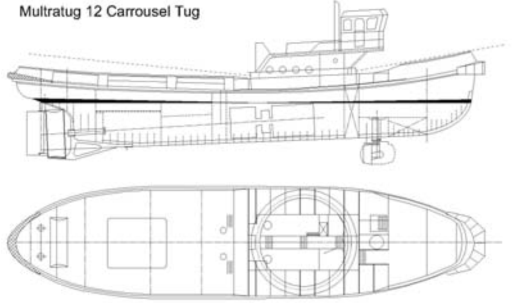

Fig. 8 Side and top view of Multratug 12 with Carrousel

L =	28.50 m
B =	6.60 m
Tbase =	2.60 m
Main Prop (CPP)	900 hp / 2.6 m
Thruster (retract.)	450 hp / 1.0 m
Bollard Pull	21 ton
Lat. Area =	≈ 60 m²

Table 3 : Main data test tug

Note: The design has a rather small freeboard, which limits the maximum hydrodynamic forces, see model results.

4.2 Model testing scale 1 : 15

Scale model tests were performed in the towing tank basin Delft University of Technology, see fig. 9 and 10. Before these test measurements, the Radio Controlled model was already tested in respect to the longitudinal position of carrousel in relation to CLR and the general maneuverability (additional skegs fitted below carrousel).

Fig. 9 Sailing ahead / wire over stern

Fig. 10 Sailing ahead / wire over side (~ 60 ton)

4.2.1 Measurements of tow-line force

A systematic variation of towing angles and sailing speeds were performed, see fig. 11. The maximum forces were limited as follows:

- At small angle of attack limited by the buoyancy of the hull (stern submerges slowly above 80 ton)
- At large angle of attack limited by the propulsion control to counter rotation.

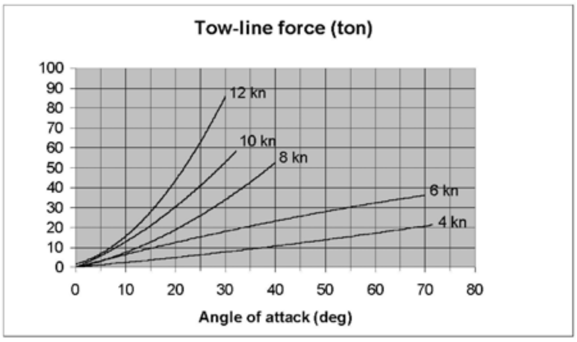

Fig. 11 Tow-line force versus angle of attack

Please note that a towline force of 85 ton results in a heeling angle of only 16 degrees !

4.2.2 Capsize test

In order to determine the behavior of the tug under increasing snap loads, the tug was pulled sideward by the towing carriage, see fig 12. The maximum measurement of the force and the heeling angle is shown in fig 13 and 14. Higher loads were not considered realistic, since the towing wire strength was already substantially exceeded.

Fig. 12 Capsize testing with sideward snap loading

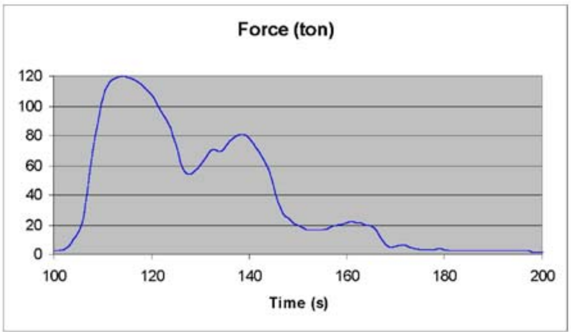

Fig. 13 Capsize test Force versus time

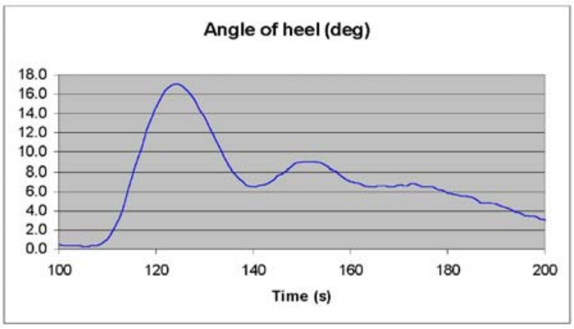

Fig. 14 Capsize test Heeling angle versus time

4.2.3 Tug performance diagram

The systematic measurements were combined in a tug performance diagram, see fig. 15. The diagram shows the large potential in hydrodynamic forces for the carrousel tug. The most remarkable part is obviously the large steering forces compared to ASD / VS escort tugs, due to the slender hull (lift drag ratio up to 9 : 1).

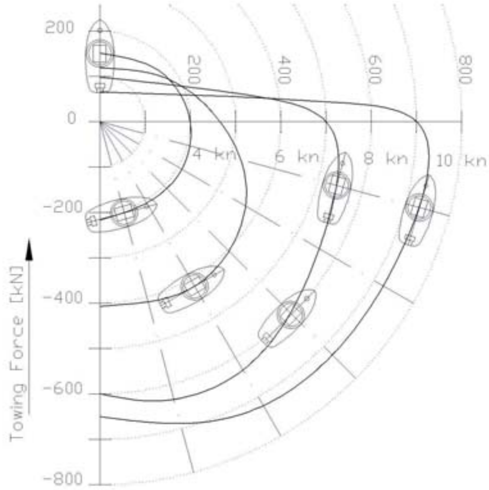

Fig. 15 Tug performance diagram

4.3 Real scale testing (progressing)

The conversion of the real tug has recently started and extensive tests are planned for this summer, aiming to validate the model results and to investigate the practical use of the system in real-life tug assistance of ships.

Video material of the real tug in action is planned to be available at the date of the conference.

4.4 Conclusions & recommendations

- The carrousel tug is an ongoing development showing good prospects.
- The lessons learned and coefficients derived from the scale model and real size testing can be used properly for newbuilding.
- Large buoyancy is of crucial importance in order to maximize the hydrodynamic forces.
- Even a narrow hull (L / B ratio 4.3) with a carrousel can properly counter capsizing loads.
- The slender hull enables a high sailing speed and a high lift / drag ratio.

5. Ship design

5.1 Mission profile

Proper design starts with both a clear knowledge and definition of the mission profile, the essential question with all new developments is related to the 'unfamiliar' design potential: What **are** the current market requirements based on the **present** operated tugs and what **could be** the market requirements when considering the **full potential** of the carrousel tug.

Often present tug limitations are considered the maximum scope of assistance – reference [5].

5.2 Clear separation of design scope inner / outer port

Tug assistance of larger ships can in general be divided into two phases:

1) At relative higher speeds (5 – 10 kn) entering port: The ship is using it's own propulsion / rudder and the tugs are running alongside with slack wires. Due to

the higher speed and propulsion power the ship can be reasonably controlled. For additional maneuverability at high speeds, only a stern escort tug can be used to steer or brake the ship.

2) At relative lower speeds (0 – 5 kn) in 'inner' port: The ship is only marginally using it's own propulsion and rudder and both the bow and stern tugs are offering additional pull (and push) to maneuver the ship to the right position. The tugs are primarily used for transverse forces on the ship and the own propulsion is used for the longitudinal force. Often however, the ship requires constant propulsion thrust on the rudder for steering and this requires an aft tug to brake constantly.

Regarding the new potential of the carrousel tug the following key words are:

I. Higher speed large hydrodynamic forces, both steering and braking
II. Lower speeds all around flexibility / focus on thrust

This leads to two different design perspectives, summarized in the table 4, fig 16 and 17 and the results thereof in table 5 below:

	Inner Port: Des. A	Outer Port: Des. B
Focus on	Thrust	Thrust & Hydrodyn.
Assistance	Low speeds	Low & High speeds
Carrousel	Above drag center	Above lift center
	In lift → stern pulled to ship	In drag → bow turned to ship
L / B ratio	Small (2.5 – 3.5)	Large (3.5 – 5)
Length oa	< 33 m (Panama)	> 35 m (seakeeping)
Hull shape	Fat & round	Sharp & slender
Lateral area	Centered midship	Over whole length
Skegs	Short twin set	Along full length
Propulsion	Twin CPP (possible FPP)	Single CPP (escorting) + bow thruster
Diameter	Large diameter	Large diameter
Steering	High Lift Rudders	Steerable nozzle(s)
Maneuvering	Easy turn stern forward	Easy turn bow forward
Full Control	Ahead	Ahead & Astern
Engine fail.	Reverse direction	Bow forward

Table 4 : Inner / Outer port designs

Pre-Design Study Carrousel	**Inner Port: Design A**	**Outer Port: Design B**
Loa =	33 m	37 m
B =	11 m	10 m
Tbase =	≈ 4 m	≈ 4.5 m
Power =	≈ 4000 kW	≈ 4000 kW
Dp =	2x 3.3 m	1x 3.9 m
BP =	≈ 85 ton	≈ 80 ton
Lat. Area =	≈ 120 m2	≈ 190 m2
Dyn.Pull. (10 kn)=	≈ 150 ton	≈ 225 ton

Table 5 : Pre-Design parameters Inner / Outer port designs

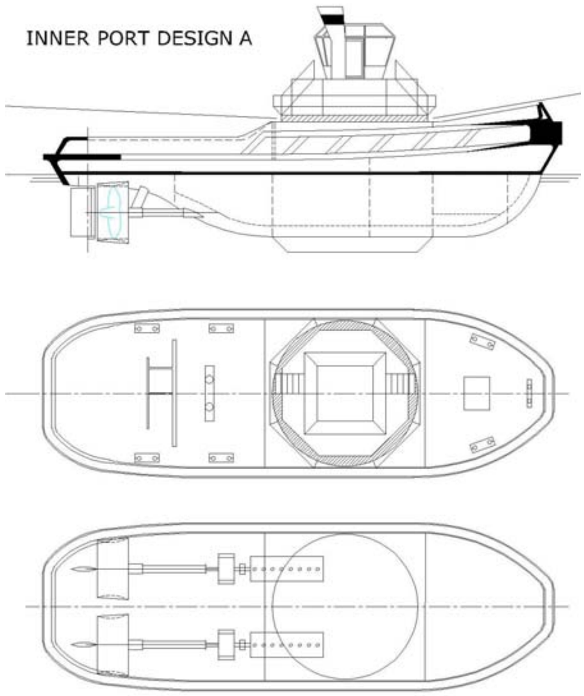

Fig. 16 General Arrangement of Inner Port Design A

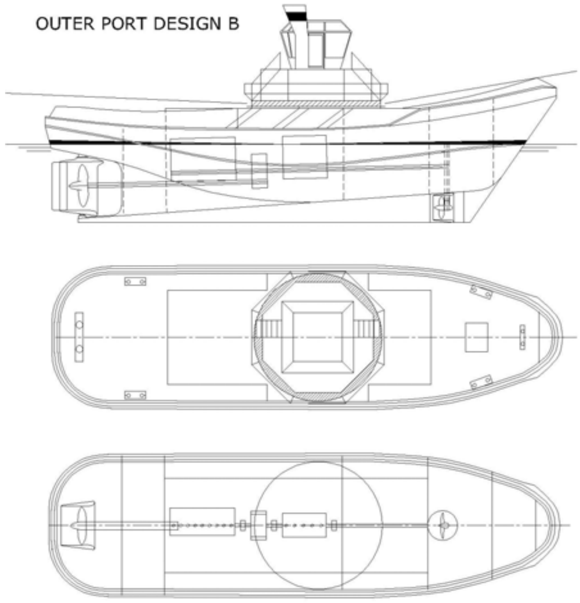

Fig. 17 General Arrangement of Outer Port Design B Combi Tug

Note: To clarify the difference in mission profile, both designs have been defined accordingly. However, designs are often multi-purpose and will be probably based on a combination of both designs.

5.3 Operational impact

5.3.1 Design A: 'Inner port'

This design can be seen as a key alternative to the ASD / tractor principle of turning the whole hull instead of only the propulsor. For full optimal thrust the hull needs to be turned with the stern towards the ship. Tug can also be fully used as bow tug.

Advantages:

- Simple and robust propulsion concept
- High propulsion efficiency by large propeller diameter and optimal free flow astern
- Stability performance of carrousel enables to increase hydrodynamic fins / skegs (if necessary)
- Use as bow and stern tug possible
- Easy braking astern tug by dragging sideward

Disadvantages

- For full bollard pull, the hull needs to be turned requiring slightly more time than turning an omnidirectional propulsor.

Summarizing: **An all-around cheap and robust propulsion concept**

5.3.2 Design B: 'Outer port'
This design can be seen as a key alternative to the (reverse) tractor tugs with hydrodynamic fins or the new generation of ASD tugs with box keels under the bow. Further design offers possibility to use features running ahead and astern and both as aft and bow (!) tug.

Advantages:

- Simple and robust propulsion concept
- High lifting / dragging forces due to attachment point near hydrodynamic center
- Stability performance of carrousel enables to increase hydrodynamic fins / skegs
- Very high Lift / Drag ratio for high steering forces at high speeds
- Running astern in Combi tug mode
- Stern and bow application possible
- Bow application enable high dynamic steering and braking forces (doubling effect!)

Disadvantages

- Longer hull requires more turning time.

Summarizing: **Large hydrodynamic forces concept**

5.4 Propulsion considerations for carrousel tug design 'Inner/Outer' port

In contrast to conventional escort tug designs, the towing line attachment point is positioned in the optimum lateral pressure center and therefore requires only marginal steering forces to turn the hull in the flow.

5.4.1 Typical tug positions
For escorting and harbor assistance in principle five conditions can be discerned for an aft tug with bow forward assisting a ship at 5 – 10 kn : see fig 18.

1) Straight behind ship in direct (arrest) mode bow forward with reversed propulsion (A)

The tug's hull is straight in line with the flow (direct mode) and the braking force is generated by reversing the propulsion.

2) Straight behind ship in indirect (arrest) mode with reversed propulsion (K)

The tug's hull is under a large angle (> 45 º) with the flow (indirect drag mode) and contributes largely to the braking force. The propulsion is partly used to control the tug's angle and partly used to counter the lift component which is 'pulling' the hull forward.

3) At an angle behind ship in drag mode with partial forward propulsion (C)

Condition similar to condition 2, but tug is moved away from a straight line behind the ship. Propulsion is primarily used to control the tug's angle, whereby the angle in respect to the ship is controlled.

4) At an angle behind ship in lift mode with partial forward propulsion (C-D)

The tug's hull is under a moderate angle (< 45 º) with the flow (indirect lift mode) and contributes largely to a combined steering and braking component. The propulsion is partly used to control the tug's angle and partly used to move forward.

5) Alongside ship in lift mode with (full) propulsion (D-E)

The tug's hull is under a moderate angle (< 30 º) with the flow (indirect lift mode) and contributes to a large steering component. The propulsion is (fully) needed to counter both the hull resistance and the lift induced drag component (increases rapidly with increasing lift).

For a so called Combi-tug design equipped with a small (retractable) bow thruster, the sailing direction can be reversed with **stern** forward. Hereby the propeller and nozzle work in their design condition with a higher efficiency than with reverse flow.

A normal Combi-tug continuously sails in this reverse direction, but a carrousel tug with a (retractable) bow thruster can change easily working direction over bow or stern without human action on deck or any time delay.

Please note that a carrousel tug connected to the **bow** of the ship can also perform condition (G), (F) and (L at lower speed), see fig. 19. This offers a completely new approach to ship's assistance for the bow tug, whereby large hydrodynamic steering and braking forces can be added to the bow of the ship !

Summarizing above conditions, the carrousel tug design requires propulsion primarily along the longitudinal axis in either forward direction or reverse direction with a wide range of positive and negative inflow speeds.

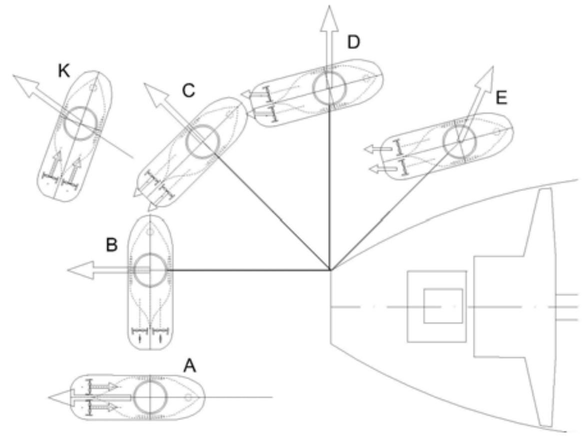

Fig. 18 Various positions for the aft tug

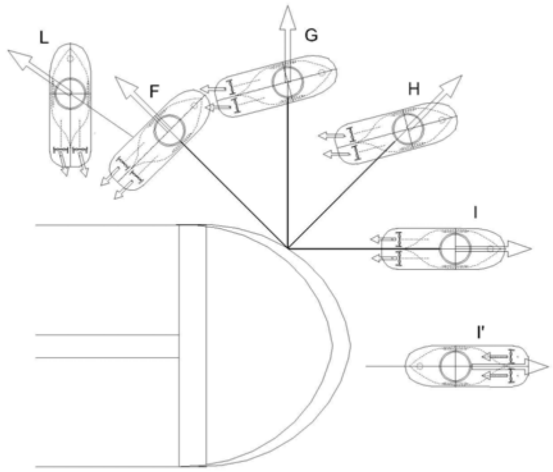

Fig. 19 Various positions for the bow tug

5.4.2 Typical propulsion results for carrousel tug

In order to quantify above propulsion conditions, a number of propulsion alternatives were selected for the carrousel tug with focus on design A) Inner port design:

- Thruster with FPP and CPP of 2800 mm
- Shaft driven FPP of 3000 mm
- Shaft driven CPP of 2800 / 3000 / 3300 mm

All propulsion alternatives are twin arrangements and driven by the same 2025 kW 1000 rpm main engines.

As typical conditions, the maximum thrust astern in condition 1 and the maximum thrust ahead in condition 5 are validated. To cover the typical (escorting) speeds, values of 6 knots and 10 knots ahead and astern were calculated, see fig. 20 (produced by John Crane-Lips).

5.4.3 Conclusion propulsion

- With same diameter, the BP of shaft FPP and CPP is higher than of a thruster
- CPP diameter increase to 3300 mm offers approx. 20% increase in BP above thruster 2800 mm.
- CPP offers similar 'braking' behavior as 180 degree-rotated thruster at lower speed.
- Optimal braking performance at higher speeds subject to further study with respect to cavitation / vibrations.
- Shaft FPP has limited reverse thrust and is less suitable for carrousel tug .

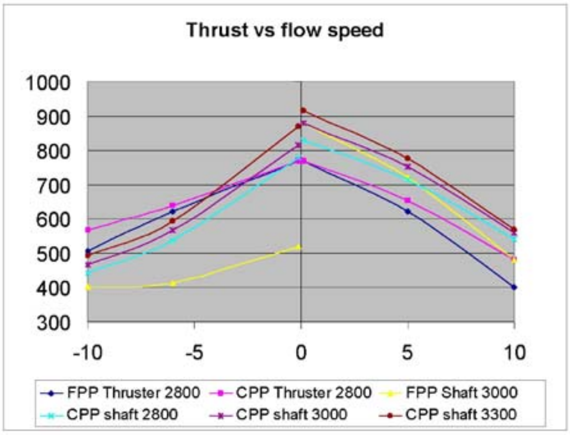

Fig. 20 Propeller Efficiency

6 Overall conclusions & recommendations

- The carrousel is an ongoing development with good prospects, offering a new revolutionary approach to connect the towing wire to the tug's hull.
- The carrousel offers two clear operational advantages of all around flexibility and large hydrodynamic forces.
- Use of hydrodynamic forces instead of propulsion reduces fuel consumption, pollution and engine running hours.
- The large stability effect of the carrousel enables to locate the towing point near the center of lateral resistance. This in return enables to control the tug's heading safely independent of towline load variations.
- The carrousel effectively prevents capsizing due to towline forces.
- Carrousel can be combined with various propulsor concepts, depending on the required application
- Combination of carrousel with conventional shaft CPP offers an attractive economic alternative, both regarding building and operational cost.
- Carrousel allows to control the bow tug safely, whilst using the full steering and braking potential.
- Preliminary design analysis shows two advantageous design concepts, one for all around flexibility and the other for maximum hydrodynamic forces. For low assisting speeds the bollard pull counts, for higher assisting speeds the hydrodynamic forces count.

- Due to bow-first sailing and the large stability safety margin, the towing operations can even be performed in adverse weather and wave conditions.

- The carrousel offers more effectiveness with less investment. The use of the large hydrodynamic forces may even lead to a reduction of the number of tugs.

- Together with increasing escorting speed, the hydrodynamic lift forces of the carrousel tug increase, thereby enabling safe operations at higher speeds.

- Substantial increase in towline forces may require additional strengthening on the side of the ship.

- Even fitting a carrousel on a conventional tug can be attractive due to the large improvements in operational performance and safety.

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