# The Rotor Tug

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Summary:
A major development in the last few years was the development of the Rotor tug. This revolutionary concept can be characterised as an enhanced tractor tug where the large skeg is replaced by an azimuthing propulsion unit. By doing this, the manoeuvrability of the vessel changes dramatically, making it excellent for its on-the-spot manoeuvring capabilities. Strategically, this concept has large advantages. In this paper, the arrangement of the vessel is described and the capabilities of the concept are described. The perceived advantages and the study points are indicated as well as how the latter are solved.

## INTRODUCTION

A call for tender for Milford Haven a few years ago gave the ignition to Ton Kooren, president and owner of Kotug International Rotterdam, for a revolutionary new type of tug.

The trigger for the new concept was to improve the performance of tugs especially in confined waters. In his mind's eye Ton Kooren then replaced the passive skeg of the traditional tractor tug by a third azimuthing propulsion unit, thus greatly improving the manoeuvrability of the tug and the ability to exert forces in all directions in a controlled manner. Although Kotug did not win the Milford Haven tender, they continued to further develop the new concept, which was soon named Rotor tug.

An intensive period then started involving the further elaboration of the idea - in house with technical staff, the captains of the Kotug fleet and research institutes. This included extensive model testing to verify and improve the concept at MARIN, the elaboration of the design and engineering at Padmos Shipyard in Stellendam including the involvement of the suppliers of main equipment and the simulations and the training of crew, pilots and harbour authorities at MSI in Rotterdam.

This paper will describe:

- the design requirements
- the ship
- the perceived advantages
- the model testing
- the simulations
- the practical experiences
- the further developments

## DESIGN REQUIREMENTS

### *Mission and operational profile*

Much attention has been given in the last few years to the development of large escort tugs. Although the necessity of these ships is appreciated, the high speed requirements have resulted in very large and long tugs which cannot be easily used in confined spaces like locks and bridge openings.

Figure 1: typical tow operation

The daily work of Kotug is assisting and escorting under circumstances of very confined spaces with large ships with high windage area like car carriers and containerships in Rotterdam and Bremerhaven. This is illustrated in figure 1.

The temptation is there to come up with large tugs. These large tugs, however, will get problems with

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their own manoeuvrability and with their inherent slow reaction time. However, needed are highly manoeuvrable compact tugs with a high power density.

*Design requirements*

The basic requirement was in fact the improvement of the economy of towing while keeping at least the same safety level. A first question for both the tug operator and the ship owner of the assisted vessel, was how the number of tugs required for a certain operation can be reduced. The more tugs are used, the more they can interfere with each other and the more crew is needed. Therefore, this leads to a required increase of the pull force per tug.

The basic requirement was then transformed towards the development of a tug as compact and handy as possible with a bollard pull of 75 t, suitable for operations in very confined areas like canals, bridges and locks, but still able to carry out other services like escorting and offshore work.

*The innovation*

Passing locks and manoeuvring in harbours takes place at relatively low speeds, say from zero up to six knots. The passive skeg as used on conventional tug designs induces that towing forces cannot be excited at any time in any direction, but that first the tug has to be positioned after which a towing force can be applied. The basic innovation of Kotug now was to replace the passive skeg by an 'active' skeg in the form of an azimuthing thruster. This idea was further elaborated into a ship with the main particulars as given in table 1.

Table 1: Main Particulars

| | | |
|---|---|---|
| Length over all | m | 31.63 |
| Length perpendiculars | m | 28.65 |
| Breadth moulded | m | 12.00 |
| Depth | m | 4.40/5.40 |
| Draught hull | m | 3.86 |
| Draught max | m | 6.57 |
| Deadweight | t | 325 |
| Displacement | t | 907 |
| Gross tonnage | t | 449 |
| Power | kW | 4700 |
| Bollard pull, 100%MCR | t | 75 |
| Bollard pull, 110% MCR | t | 79 |
| Speed | Kn | 12.5 |

Once the basic idea was realised in the ship, the new concept turned out to have more inherent advantages, which can be seen from the viewpoint of towing operations, reliability and economy.

*Improved towing operations*

- A breath taking manoeuvrability: turning on the spot, very fast response when moving from PS to SB, side ways moving (see figure 2)
- Moving sideways at 6 knots, this opens the possibilities to sail with the assisted ship in the right position for turning without exerting any pull when not needed (see figure 3)
- Possibility to use almost full power when pushing side to side, this is very useful in confined waters like locks and canals
- Division of the required power over three thrusters resulting in lower draught or lower power per thruster with higher efficiency.
- No danger of damage to propellers when positioning in bulbous bow area compared with stern drive tugs
- A smaller chance on damage caused by tow lines in the propulsion unit while disconnecting the tow lines.

Figure 2: Turning on the spot

Figure 3: Moving sideways: crabbing at 6 knots

*Reliability and environment*

- High redundancy: towing still possible after black out of any one of the units
- Possibility to sail with one unit/engine when idling or free sailing resulting in better loading of engine with lower emissions

*Improved economy*

The improved towing possibilities, the high bollard pull in a relatively short vessel and the high redundancy of the three-propeller concept leads to a smaller number of tugs required to perform a certain towing job.

But, as the model tests confirmed, the tug is also able to perform escort services over the bow up to 10 knots and up to 8 knots over the stern.

## THE SHIP DESIGN

*Hull*

The hull form has been derived from the proven hull form of the current fleet of Z-drive tractor tugs of Kotug. The hull form is characterised by sharp bilges and straight frames. The rise of floor allows easy sideways movement. Three small parallel skegs have been fitted for directional stability. The hull is heavily built with scantlings and steel plates 20% above class requirements.

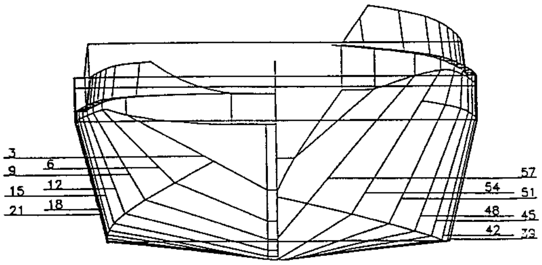


Figure 4: Lines plan of Rotor Tug

*General Arrangement*

Much emphasis was given to an appropriate appearance of the ship. In our opinion, the result is pleasing to the eye and a design that can be easily recognised as a Kotug ship. There is spacious and comfortable accommodation for 7 to 10 persons, though normally the tug will be operated by only three persons.

*Towing equipment*

The hydraulic towing winch has a pull of 30 t at a speed of 0-15 m/min or 13 t at 0-30 m/min in the first layer and has a holding power of 200 t. The winch has two drums for harbour towing with a capacity of 200 m of 56 mm steelwire each, and one drum for offshore towage with a capacity of 650 m of 56 mm.

The towing/escorting/anchor winch on the foreship has the same pulling power and is suitable for 200 m 56 mm steelwire.

*Firefighting equipment*

The firefighting pump has a capacity of 600 $m^3/h$ at 18 bar and is driven by one of the main engines. The existing ships can easily be converted to comply with FiFi 1 requirements.

*Power generation*

The three main propulsion engines are of make Caterpillar, type 3516 B DI-TA, with a power of 1566 kW each. The engines are coupled via a twin disc machine control drive (MCD) type 3000-2LD to the azimuthing fixed pitch propellers with nozzle of Schottel, type SRP1212FP. The propellers have a diameter of 2150 mm and are optimised for towing.

The main engines are flexibly mounted to reduce noise and vibrations. Each engine can be easily replaced through flush mounted hatches in the main deck. One complete engine can be replaced within 48 hours if needed. The tank capacities are as given in table 2.

Table 2: Tank capacities

| Tank Capacities | | |
|---|---|---|
| Marine diesel oil | $m^3$ | 170 |
| Lub oil | $m^3$ | 9 |
| Fresh water | $m^3$ | 25 |
| Water ballast | $m^3$ | 113 |

*Controls*

Much emphasis has been placed in the design phase on the ergonomics of the controls, because the captain had to control three independent controls with two functions (direction and revs) each, so in total six functions. The captains were used to operating two independent thrusters and now had to add a third one in their mind. Schottel invested much in the design and layout of the joystick controls and possible cross connections. The consequences of a breakdown of one of the propulsion units had to be considered carefully. In actual practice controlling the tug proved to cause no problem at all and before long the captains had full control over the three thrusters. The third thruster is normally in mid position and only special manoeuvres require separate controlling.

## HYDRODYNAMIC ANALYSIS

Apart from the advantages of the tugs already stated, there are some aspects that needed deeper study. By means of research, the risky aspects had to be addressed and quantified. This enabled a good verification of feasibility of the concept in the following areas:

- Powering characteristics at full speed and at bollard pull and the effect of the three thrusters close to each other
- Course stability
- The escorting and handling abilities

Together with the Foundation for Dutch Maritime Research, an investigation was started towards the feasibility.

In general, these investigations have a simple approach: calculate what you can calculate and use model tests to achieve the other issues. However, the hydrodynamics of a tug are often so complicated that not many calculations are possible. Model tests are therefore necessary. The use of model tests is not only very useful to obtain insights in forces and moments on the ship. The model actually demonstrates the feasibility. The convincing power from these model tests is an important aspect.

The model tests demonstrated how the idea could work in reality in a straightforward matter.

MARIN has much experience in carrying out projects for many tug designs on a commercial base. Apart from escort tugs, this includes sea and inland tug-barge combinations, salvage tugs and other workboats. Projects concern calculations and simulations, model tests and full-scale measurements. Tests do not only concern the resistance and propulsion characteristics, but mainly the manoeuvring and escorting capabilities, the behaviour in waves as well as the capability to perform dedicated tows and operations. An impressive range of model basins and simulators is available for this. This brings us to an important synergy between model tests and simulators.

Model tests are not only to verify the concept, but give input to the construction of a numerical manoeuvring simulation model: the mathematical model. These models form the basis for simulation work. In these simulations, the tugmaster can learn to handle the tug and obtain the correct look and feeling for his future escort tug. For tugs, the tugmaster is an important part in the control loop. After all, the only person to discuss the handling capability of the tug is an experienced tugmaster. Therefore, especially for these ships, mathematical models are constructed that can be used to perform many calculation and scenario simulations.

*Stability*

Due to the low centre of gravity and the relative large breadth the Rotor tug has an excellent stability with a metacentric height of more than 2 m. Also due to the position of the towing points at the extreme ends of the ship, the ship is naturally turned out of possibly dangerous athwartship positions, like all tractor tugs.

This has been checked in the model tests where the following tests were performed:

- escorting over the stern at 4, 6 and 8 knots
- escorting over the bow at 4, 6, 8 and 10 knots

During none of these tests dangerous situations occurred and the captain had control over his ship on a model scale, which is even more difficult than on real scale.

*Prediction of speed/power*

With this kind of unconventional arrangement it is almost impossible to accurately predict the speed power relation by calculation. This is due to the unknown influences of wake and thrust deduction for propellers below the ship, the mutual interference of the thrusters and the behaviour of appendages like docking tables. Model tests have been performed showing a speed potential of about 13 knots with the installed power.

In a later stage the design of the propellers was modified in favour of more pull at lower speeds. During trials a speed corrected for water depth and wind and waves of about 12.5 knots was obtained. The speed with two thrusters running was 10 knots and with one thruster 8 knots.

*Prediction of bollard pull*

A complication in the prediction of the bollard pull was the interference between the fore and aft propellers. During model tests a variation in azimuthing angle was investigated ranging between 20 degrees outward and 15 degrees inward.

The result was that the optimum angle for the forward thrusters was 15 degrees outward. This was confirmed on the full-scale trials. The official recorded bollard pull at the nominal power of the engines was 75.2 tonf. At 10% overload a bollard pull was achieved of 79.3 tonf.

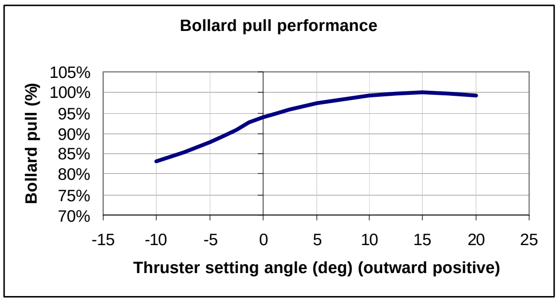


Figure 5: Bollard pull versus thruster angle forward thrusters

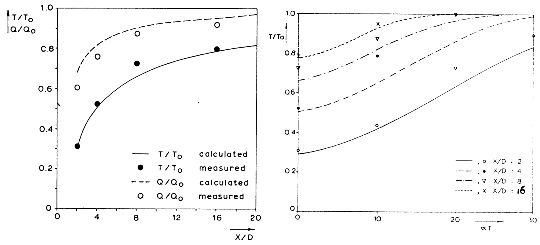
*Powering and thruster interaction*

The application of three azimuthing thrusters close to each other induces many challenges. The application of these under the hull of a tug is even more challenging. In the following, it is described how the feasibility is verified.

The application of a large beam is beneficial for the transverse stability and hence for the escorting capabilities, both in direct and in indirect mode. The attained heel angle is in fact the limiting factor in the escorting mode. Therefore, a large beam is selected. The large beam puts forward some challenges with respect to the resistance of the vessel and the course keeping ability. Ships with a low L/B ratio have a tendency of being naturally course unstable. The steering forces of the vessel should be sufficiently large to be able to check unwanted yawing motions. In addition, the wide body of the ship will yield high wave resistance at higher velocities (the ship will generate high waves). This is the same for all tugs, but particularly with the current L/B of 2.39 and Froude number of up to 0.4 at 13 knots.

The choice for a developable hull form is governed by the ease of manufacturing of the hull, resulting in a hard chine hull form. From a resistance point of view, the chine lines have to be as much in the flow direction as possible in order to avoid flow separation or undesired vortices.

Figure 6 gives an illustration of the generated wave pattern by the vessel for service speed according to calculations, model tests and full scale measurements.



thruster-thruster interaction under a flat plate as: a) a function of distance between the two thrusters; b) a function of azimuth angle of the forward thruster

Figure 7: Mutual influence between azimuthing thrusters

There is a risk at undesired interaction between the three azimuthing thrusters. The distance between the thrusters is low. This results from the restricted ship length and that from a construction point of view, the thrusters are already located in the aftmost and foremost positions. The length-wise distance between the two thruster positions is approximately 12 meter or only 5.5 propeller diameters. Figure 7 (from [1]) shows that already at a distance of 20 propeller diameters, considerable interaction is present. This could manifest itself in an thrust efficiency decrease of 45 percent for a distance of 5.5 diameters between the thrusters, when they are in line with each other. Due to the fact that the thrusters are located in triangular set-up, improvement is obtained. Further alignment is obtained by optimising the bollard pull.

For the rotor tug, the choice of the most optimum angles for efficiency is based on model tests. With these settings, a good performance is obtained, certainly better than the efficiencies indicated in figure 7.

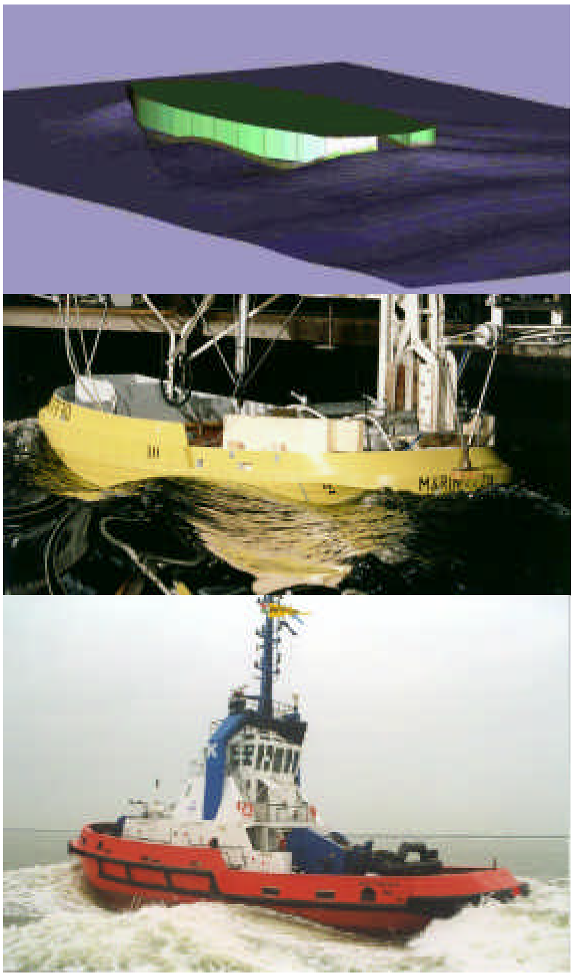


Figure 6: Comparison of wave patterns in three different stages: calculations, model scale, full scale

*Course stability*

The inherent course stability of the vessel itself is assumed to be poor, because of the deletion of the skeg. However, the ducted azimuthing thruster at that location is also delivering a transverse force. It is of interest to compare the transverse force of this thruster to the force generated by a suitable skeg. In figure 8, a comparison is made between transverse forces generated by a skeg and a thruster for angles of attack between 0° and 50°. It shows that for higher drift angles, the transverse force on a thruster is lower than the hydrodynamic lift and cross flow drag as created by a centre line skeg.

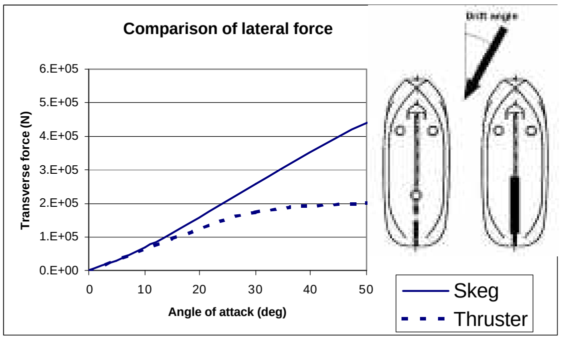


Figure 8: Lateral force due to thruster or skeg

However, for lower drift angles, forces are of the same order of magnitude. The forces at low drift angles are important for the course stability. As transverse forces are comparable in magnitude, the course stability on the vessel is sufficient. This is confirmed by the observations on the ship that indicate that the foremost thrusters are used for steering when sailing at service speed. During ship handling, most of the time the ship is most of the time used as a tractor tug. However, other modes are also possible. The tug is then steered with the other two propellers (one front and one aft propeller).

*Escorting capability*

After establishing the effects of resistance and propulsion and the suitability of the course stability, it was obvious that a harbour tug is created that was able to combine excellent manoeuvring capabilities with a high bollard pull as put forward in the initial requirements. The operational advantage of this is evident and was explained earlier.

The next question dealt with the utmost limits of the vessel. In the aftermath of oil pollution disasters like the Exxon Valdez, legislation has been changed. Greater attention has been devoted to escorting at high speeds. Tugs are used particularly in indirect mode to be able to generate large steering forces or braking forces or both on a “disabled tanker”. If the Rotor tug were able to generate these forces as well, an important goal would be achieved. Therefore, the actual performance under escorting conditions is verified with tests with the tug under escorting condition in the towing tank.

During the model tests it was shown that the model could be kept controllable in the escorting situation. Moreover, it was shown that escorting over the bow and over the stern was possible. This is a vast perceived strategic advantage. The common way of operating a tractor tug is escorting over the stern. However, in higher waves, green water on the aft deck is making it hard to escort over the stern. In those cases, the sailing direction can be reversed and escorting can be done over the bow.

It even proved that escorting in direct and indirect mode was possible over the bow and over the stern. In figure 9, a number of equilibrium positions, obtained during model testing, are shown. A remarkable observation was that almost the same steering and braking forces are developed, with the tug under completely different sheer angles and the thrusters are under completely different angles.

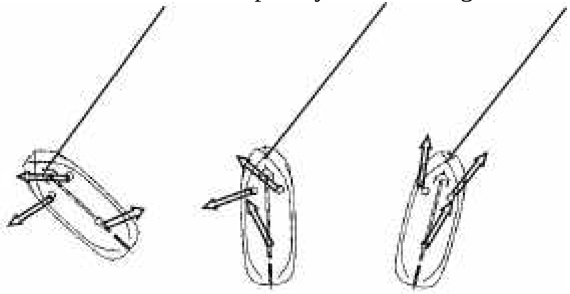


Figure 9: Different equilibrium positions of the rotor tug while escorting over the bow at 6 knots with a towline force of about 90 tonf.

Apparently, the use of the three thrusters in direct mode is giving as much tow line force as indirect towing. This means that more equilibrium positions are found while simulating. It also means that the tugmaster has the liberty to choose an appropriate equilibrium position during his escorting work, according to his experience, preferences and environmental conditions.

The liberty to choose between several equilibrium positions is a vast advantage. Particularly when escorting is required in heavy seas, since the indirect escorting mode can be dangerous. In high waves, escorting cannot be pursued up to the maximum heel angle, since the risk is much too high. This means that for a tug, the escort assist diagram based on the indirect mode, a considerable degradation of this diagram is expected when sailing in waves. If tug assist forces of the same magnitude can be generated in direct mode, a vast advantage is obtained.

The issue of escorting capabilities in waves has not been investigated yet (although several experiments have already been carried out). In the future, this will be a major research item.

*Simulations*

In 1970, one of the world’s first full mission bridge simulators was installed at MARIN, and since then they have gained experience with mathematical modelling. Up till today this has been extensively used and updated for several purposes, including the training of tugmasters and the training of risky operations. The linking of simulators is important for the trainings considered here. The co-operation between pilots and tugmasters can be verified, either for very critical operations (as for example the tow-out of the Troll field) or for new tug concepts. Furthermore these simulations come up with the necessary number of tugs for certain operations. Examples are shown in [4]. Critical in the mathematical model is the description of the propeller hull interaction for tugs. In the past, many mathematical models were published in which the manoeuvring or escorting capabilities were described as the summation of the forces on the hull of the ship and the open water characteristics of azimuthing thrusters. However, these simplified mathematical models have proven to be insufficient as for example reported in [3]. Due to the thruster-hull interaction and the thruster-thruster interaction many discrepancies have been found, even as much as 100%. Therefore, a comprehensive calculation procedure should be present with a modular description of hull forces, thruster forces and interaction forces. Model tests provide the necessary input for this.

This simulation procedure is also needed to verify the escorting tests. During the model tests in escorting conditions, the following items are shown:

- The ship could manoeuvre to its escort location from the tow-line pick up spot.
- The towline force (steering and braking forces) have been measured and is high

However, this towline force is based on the consumed power, which is unlimited during model tests. Therefore, a direct creation of tug assist diagrams based on the measurements is not realistic and would give too high results. Since a true comparison has to be made, the results are adjusted numerically to the correct power. The model tests and the simulation model are used for this. Results are shown in figure 10. These tug assist diagrams will be validated by full-scale measurements in the future.

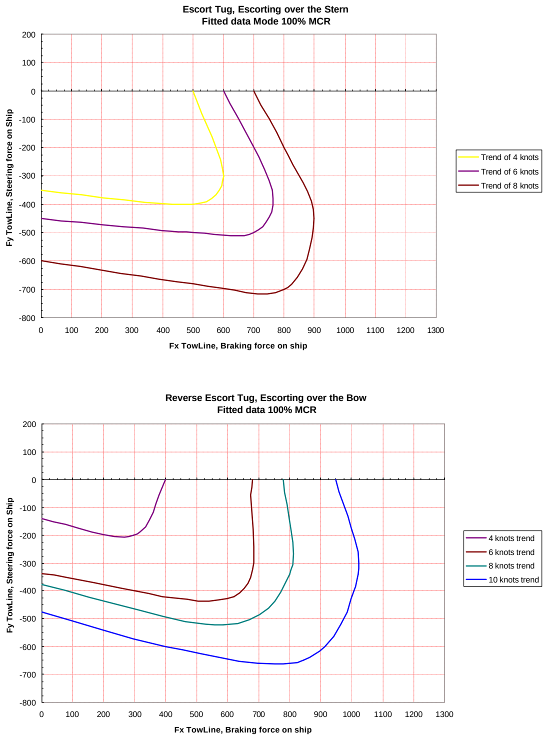


Figure 10: Tug assist diagram for assisting over stern and bow respectively

The main advantage of a suitable mathematical model is that not only tug assist diagrams can be adjusted very well, but that simulations can be carried out with a man-in-the-loop, of as was the case here: with many men in the loop (see figure 11). The simulators at MSR are used to for the training of tugmasters and pilots.

Since the rotor tug had new capabilities in operating mode, the training had their purpose in the development of a towing strategy for the rotor tugs.

This simulator set-up had great impact in convincing the harbour authorities and pilots that the Rotor tug was capable of carrying out escorting and ship assisting jobs in various environmental conditions.

Figure 11: Example of tug escorting a tanker in a bridge simulator at Marin.

The use of the simulator in the training of the captains enabled to create a mock-up of the steering console of the Rotor Tug. Schottel managed to do this job, installing the complete steering console of one of the Rotor tugs “RT Magic” and to integrate it in the bridge simulations at MSI in Rotterdam.
In figure 12, this optimised console is shown.

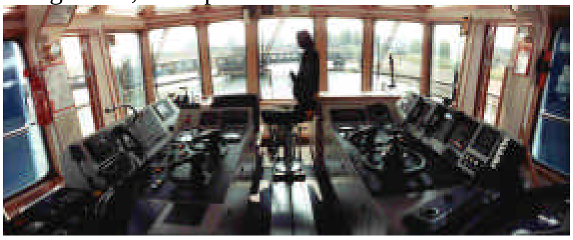


Figure 12: Bridge console of Rotor tug.

## COMPARISONS

When the feasibility in terms of resistance, bollard pull and tug assist capability handling, are described it is significant to compare the capabilities of the concept to existing tug designs from literature.

*Bollard pull versus length*
The current concept is compared with existing vessels. It is especially interesting to compare the bollard pull in relation to length as shown in figure 12.

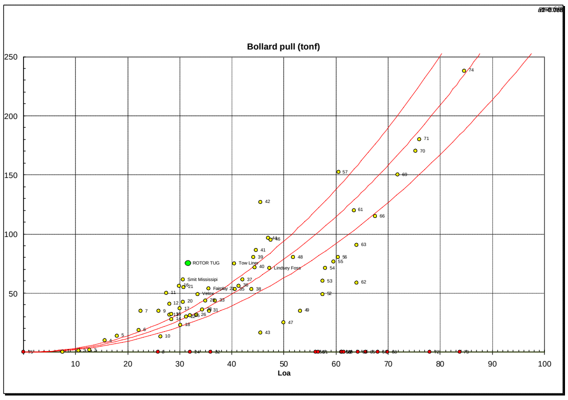


Figure 12:Bollard pull versus length

It is clearly shown that the Rotor Tug has a very high bollard pull in relation to its length.

*Bollard pull versus power*
A comparison is made taking into account the propeller diameter using a Bendemann factor as follows:

$$Pull = f \times (P \times D)^{2/3}$$
$$with:$$
$$P = power\ (kW)$$
$$D = propellerdiameter\ (m)$$
$$f = coefficent$$

This shows a favourable bollard pull taking into account the interaction between the fore and aft propellers.

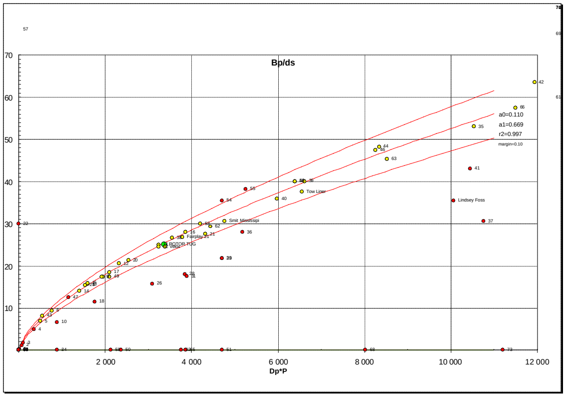


Figure 13: Bendemann factor

*Displacement versus length*
Due to the relatively large breadth the Rotor tug relatively can still accommodate a useful displacement within its short length and has both sufficient weight and metacentric height available to counteract the large towing forces.

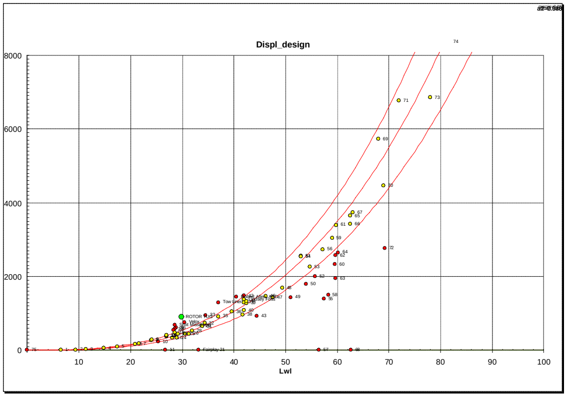


Figure 14: Displacement versus length

*Speed versus length*

During the model tests the speed potential of the tug turned out to be about 13 knots. After model tests the decision was made to optimise the concept for pull at moderate speeds. After modification of the propeller and nozzles to favour the pull, the speed turned out to be a still satisfactory 12.5 knots.

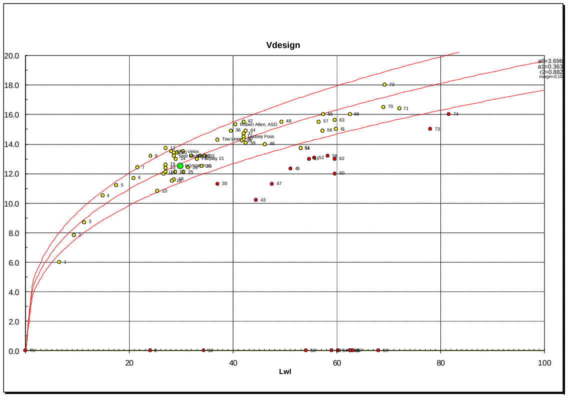


Figure 15: Speed versus length

## CONCLUSIONS

In this paper the concept of the Rotor tug is described. Reasoning from an operational profile, a mission is defined. In this mission, a compact tug with excellent manoeuvrability was essential. The concept of the rotor-tug combined this on the spot manoeuvrability requirement with a very good bollard pull and even with very good escorting capabilities.

By addressing certain study points in an early stage and considering model tests and simulations, the concept was extensively verified. It showed that the initial design requirements were met. Moreover, the results had such a convincing power that by a good combination of model-tests and simulations the effectivity and the practicality of the new concept was shown.

Working on this project was certainly challenging for all participants. It showed that in the end a new tug type has been developed in the Netherlands. Many of the early reservations could be turned into advantages and the tug can be considered an operational success.

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