The Carrousel-RAVE Tug – Design Development of a Unique High-Performance Ship Assist/Escort Tug

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SYNOPSIS
The Carrousel-RAVE tug concept is a unique, novel development in the tugboat industry. The design is a joint co-operation between Robert Allan Ltd, Voith, Novatug and Multraship. The prototype design is for a compact, 70-tonne BP vessel combining a Carrousel system with an in-line Voith Schneider Propeller configuration. With this arrangement, the tugboat can efficiently generate high forces when assisting and escorting ships by utilising the hull's own hydrodynamic characteristics, while using minimal thrust. Controllability and manoeuvrability of the tug are also enhanced, and operations in confined spaces can be executed effectively. This design is the culmination of several years of extensive numerical modelling, theoretical predictions, simulations and model tests. Experienced tug master feedback is very positive with regard to the ease of controllability of the tug and its ability to effectively perform a plethora of operations.

INTRODUCTION
The Carrousel-RAVE tug concept is the culmination of many years of experience, research and innovation by three main companies: Robert Allan Ltd of Canada, Voith Turbo Schneider Propulsion GmbH & Co of Germany, and Multraship of the Netherlands. The design combines the Carrousel towing system designed by Novatug and installed by Multraship on its ***Multratug 12***, with the unique longitudinal in-line Voith Schneider Propeller configuration pioneered by Robert Allan Ltd and Voith.

The Carrousel system has been described in papers presented at previous *ITS* and *Tugnology* conferences, beginning in 2002[1]. Designed and patented by Novatug BV, the system comprises a compact and lightweight towing winch rotating around a circular track, counterbalanced by a hydraulic power pack.

The main advantage of this system is that the tow point moves to align with the direction of pull, which, when pull is athwartship, vastly increases tug stability by decreasing the heeling moment caused by towline forces. As such, the tug can safely operate in a broad spectrum of manoeuvres and create steering and braking forces generated by the tug's own hydrodynamic characteristics which are higher than would be the case in a conventional towing configuration. *Figure 1* illustrates the effect of the Carrousel system on towline heeling moment.

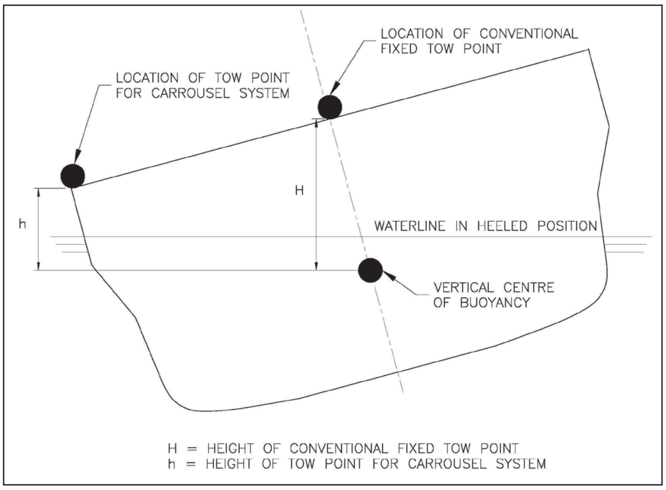

Figure 1: Carrousel system effect on heeling moment

The RAVE configuration has also been detailed in previous publications since its public introduction at *Tugnology '11*[2]. The concept features two Voith Schneider Propeller (VSP) units arranged longitudinally inline. This unique arrangement provides enhanced control and manoeuvrability of the tug in any heading (ahead, astern, sideways), enabling the tug to operate efficiently and effectively even in very confined spaces.

The combination of the Carrousel and RAVE concepts required extensive testing to ensure the viability of the concept. Rather than rushing into actual construction to verify initial predictions, it was decided to examine all aspects of the performance of the concept and to gain a full understanding of any potential limitations, particularly with respect to the separation of the drive units. Initial trials were performed using CFD methods and then with experienced tug masters in the Voith simulator. Further model testing was undertaken to fully understand the behaviour of the tug and also help determine the optimal arrangement of appendages and towing equipment location. All results were quite positive. Qualitative feedback from tug masters confirmed that the tug was directionally stable, and very easy to manoeuvre and control. Quantitatively the design achieved 70 tonnes bollard pull, and 160 tonnes of steering or braking force.

Satisfied with the performance predictions, and armed with a thorough understanding of the behaviour of the RAVE concept, the design team moved into top gear and developed the final arrangement of the prototype tug, optimising for maximum safety and controllability. The following paper details that design development testing process from initial to final phases, and describes the design to date.

THE CARROUSEL-RAVE TUG DESIGN CONCEPT

Carrousel tug concept

The advantage of a Carrousel tug when working as a stern tug during braking manoeuvres is immediately obvious. It can position itself directly behind the assisted vessel in a transverse position (yaw angle almost 90 degrees), and thus use the hull's lateral resistance to create high braking forces.

Figure 2: Example of Carrousel tug in transverse position behind assisted vessel (prototype Carrousel tug **Multratug 12***)*

However, working on the stern often involves steering assistance as well. A Carrousel tug can do this in a similar manner compared to other tugs, with the added benefit of being able to safely choose the tug's heading in such a way that the lateral resistance and towline forces are of the correct magnitude and are pointing in the right direction at all times. When a combination of steering and braking is desired, the towline angle relative to the assisted vessel heading can be 135 degrees and the tug's heading can be perpendicular to the towline. In this situation the steering and braking forces are equal. If more steering is required, the 135-degree angle is gradually decreased to 90 degrees by repositioning the tug. Here, a combination of balancing the tug's heading (and so manipulating the lateral resistance) and choosing the optimal propulsion forces enable the tug to create the required steering force.

When working as a bow tug, the advantages of the Carrousel tug are perhaps less expected but even more significant. The tug can work on the bow of the assisted vessel at towline angles close to, and even over, 90 degrees with respect to the vessel's heading. When the tug is sailing alongside in the same direction as the assisted vessel, there is hardly any towline force interaction. However, when assistance is required, the captain can 'open up' by steering away from the assisted vessel with the tug's bow, thus creating lateral resistance resulting in steering forces. By letting the tug drop down behind just a little, and thus increasing the towline angle over 90 degrees, the tug will create additional braking forces. This means the bow tug can assist not only in steering, but also in braking the assisted vessel. This manoeuvre is illustrated in *Figure 3*.

Figure 3: Working as a bow tug, letting the tug fall behind and create steering and braking force (prototype Carrousel tug **Multratug 12***)*

RAVE tug configuration as a base for tug equipped with Carrousel system

As described above, the Carrousel tug characterises itself by using mainly the tug's own hull resistance to create the required forces. The propulsion system is used merely to control the tug's heading, position and speed. Simply put, at a given operational speed, it is the tug's heading that determines its resistance through the water and thus the magnitude of the towline force.

Keeping in mind that assistance is possible on the bow and stern, the propulsion system should be utilised to optimise the tug's controllability and control its heading. An arrangement having a propulsor on each side of the Carrousel system generates the highest moment to control the heading. The farther these propulsors are placed away from each other, the greater the moment. However, the inflow angles to the propulsors can become very large, the worst case being when the tug is being dragged transversely through the water and the water into each propulsor is coming from the transverse direction.

Z-drive propellers also act as rudders, so when the unit rotates, the entire propeller and thrust turn with it and exert thrust forces in intermediate directions between the initial and final unit orientation. The additional effect of this is that the nozzles' and propellers' lateral profiles change when the unit is turning relative to the flow direction, which can lead to sudden changes in resistance at the position of the thruster and a rapid change of heading of the tug. This can be counteracted with the propulsion forces, but in the meantime results in fluctuations of the towline force.

By using VSPs the above concerns are eliminated. VSPs are inherently able to maintain performance in a fluctuating inflow without risk of stalling the propeller or visible thrust deduction. The time to change thrust direction is also much faster than with a Z-drive. Therefore, an optimal propulsion system for a Carrousel tug is two Voith Schneider Propellers, located on either side (forward and aft) of the Carrousel system: enter the RAVE tug!

Originally introduced at *Tugnology '11*, the RAVE tug concept features a longitudinally in-line VSP arrangement. This separation of the VSP units enables generation of the highest moment to control the tug's heading, while adding operational capabilities not common for other type of tugs. To summarise, the RAVE tug can:

- generate maximum thrust through 360 degrees;
- apply force through the hawser when under way by sidestepping without orientating the tug along the direction of force. It is possible to control the assisted vessel position at low speed in confined spaces or canals with very narrow passage;
- operate alongside the assisted vessel in transit using the Carrousel system, and be capable of applying practically the same force inboard by fender contact, and outboard by hawser, or along direction of movement if towing or braking is required;
- apply direct pressure in any orientation to the vessel during docking operations (breasting). If force is applied sideways, pressure to the assisted vessel is minimal and the tug can use maximum thrust without danger of damage to the assisted vessel;
- perform manoeuvres or change orientation without any fluctuations in the applied force during assistance;
- can hold station in any tug orientation to current, wind and wave direction, and can also hold station against fi-fi monitor reaction forces;
- a tug can be sucked to the hull when working in close proximity to the bow of an assisted vessel, where pressure distribution changes dramatically in a short distance along the hull. The RAVE tug has the capability to quickly (in 3-5 seconds) apply side thrust and sidestep from such a dangerous zone, parallel to the direction of movement;
- seakeeping is improved because of pitch and heave reduction. This reduction of motion is the result of damping effects of the propeller guards. The RAVE configuration enables uniform distribution of these damping forces along the hull.

Operational design requirements of Carrousel-RAVE concept

As the owner of the first Carrousel-RAVE tugs, Multraship's design requirements were as follows:

- Harbour tug size, limited to max 32m length and < 500gt;
- Static bollard pull requirement min 70 tonnes
- Dynamic escort steering/braking forces requirement: to challenge the strongest dedicated escort tugs currently on the market;
- Minimum free-running speed of 14 knots.

Since a well-designed Carrousel tug can generate very high dynamic forces, it was believed to be possible to design a great escort tug in a harbour tug size, which could also still operate in locks and the relatively limited spaces of the proposed operational area. The first tugs to be constructed are planned to operate in the Westernscheldt area, which includes the Canal Ghent-Terneuzen and the Port of Antwerp.

CARROUSEL-RAVE TUG INITIAL FEASIBILITY ASSESSMENT

Simulator studies

At the beginning of the development of a RAVE tug combined with the Carrousel system the first question posed by all parties involved was: How will a RAVE with a Carrousel system perform? The pure RAVE concept had already been studied intensively by means of model tests and CFD calculations[2], but how it would work in combination with the Carrousel system was unknown. Of course there had already been many successful trials with the Carrousel tug ***Multratug 12***, as well as theoretical analysis, supported by general force calculations.

At an early stage of design the ideal way to gain a deeper understanding of how the RAVE tug will perform with the Carrousel system is through extensive testing in a manoeuvring simulator[3]. Voith has its own manoeuvring simulator (SimFlex from Force Technology)[4], where two vessels can be actively driven and interact by towline and fender forces *(Figure 4 on next page)*. If the vessel model is established in the simulator, then the best way of testing the concept is by experienced tug captains performing real life operations in the virtual world.

The simulator model consists of three main parts:

- The hydrodynamic model of the RAVE, including propulsion system and engines;
- The visual model of the tug;
- The model of the Carrousel system.

Figure 4: Voith's manoeuvring simulator with two bridges

The hydrodynamic model

The hydrodynamic model has been exclusively designed by using computational fluid dynamics (CFD). To do this, a CFD model was created and numerous non-stationary and stationary calculations of the tug were performed. The results of the calculations are comparable to a traditional planar motion mechanism (PMM) test. The traditional PMM tests, which are carried out in model basins, are well known. There are several advantages in carrying out the development of the hydrodynamic simulator model by CFD and thus avoid scale effects, because the calculations were done in full scale with the possibility to develop a simulator model without owning a PMM. *Figure 5* shows a CFD result of a RAVE tug where the pressure field and the wave pattern at 10 knots, including the VSPs, are plotted.

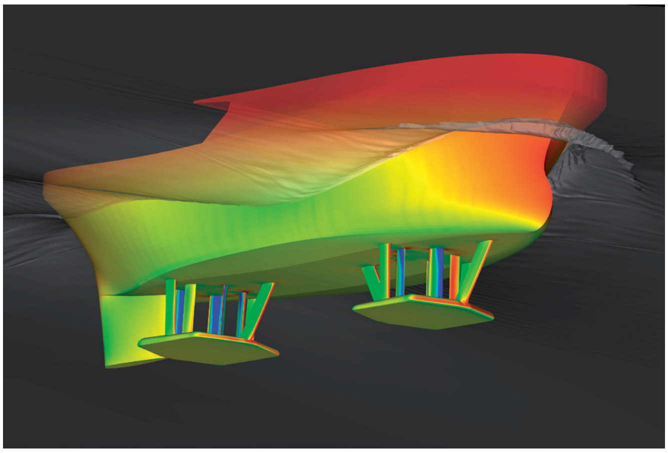

Figure 5: Pressure distribution and wave pattern of a RAVE tug calculated at 10 knots

The hydrodynamic model consists of the forces of the hull and the thrust forces of the two VSPs, including the effect of the thrust plate (VSP guard). The following effects are considered:

- Interaction between the VSPs and the ship hull (by suction forces);
- Interaction between both VSPs;
- Interaction between the thrust plate and the VSPs;

Figure 6 shows an example of the calculated interaction – showing velocities – between two VSPs.

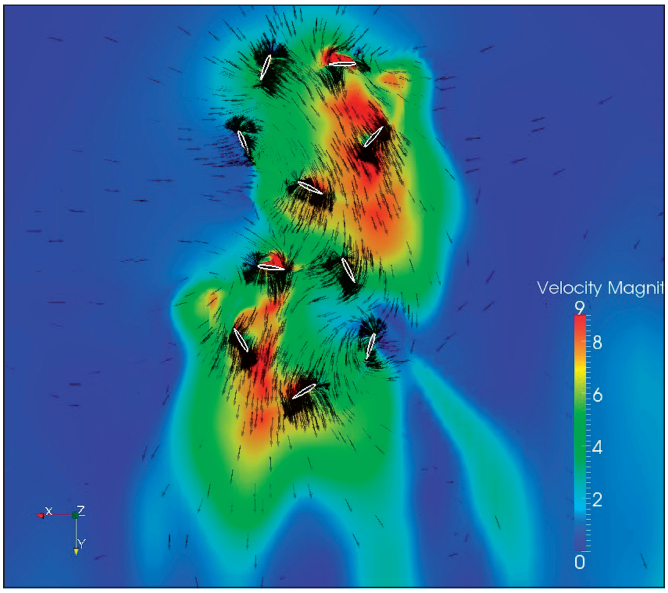

Figure 6: Interaction of two VSPs calculated by CFD

An important factor is the incorporation of the Carrousel system into the simulator. This was done by computing the difference of towline force and moments of a Carrousel system compared to a fixed connection point as simulated by the original hawser. *Figure 7* shows the implementation of the Carrousel system in the simulator model in the horizontal plane.

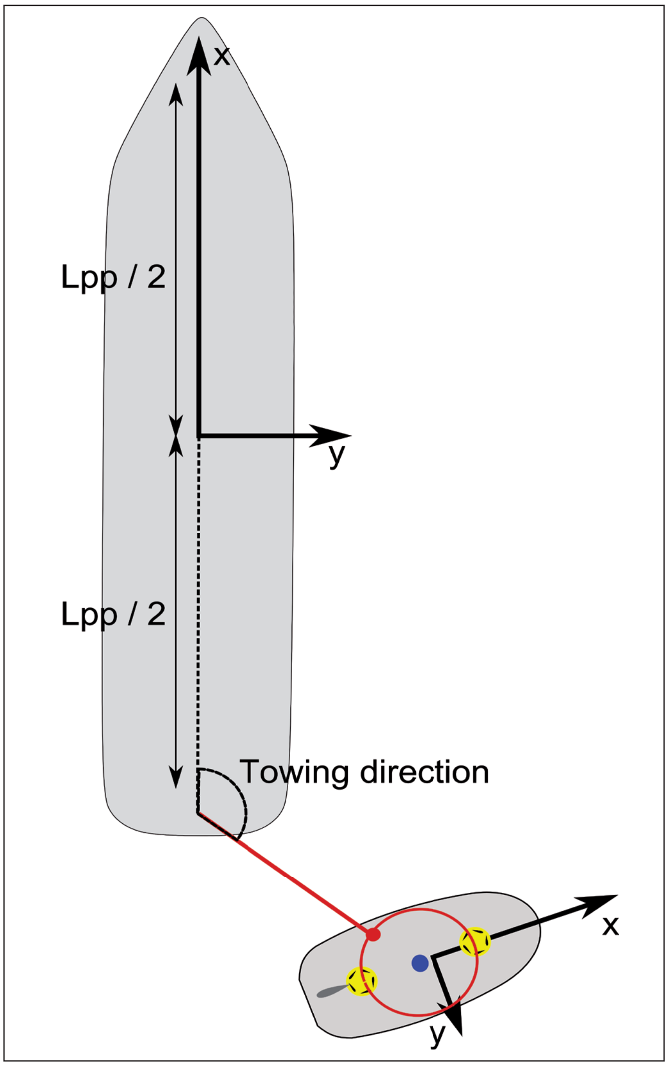

Figure 7: Definition of winch co-ordinate system

The attack point is shifted according to the diameter of the Carrousel system, and this can be seen in *Figure 8*. The Carrousel system is free to rotate the horizontal force component in the tug co-ordinate system.

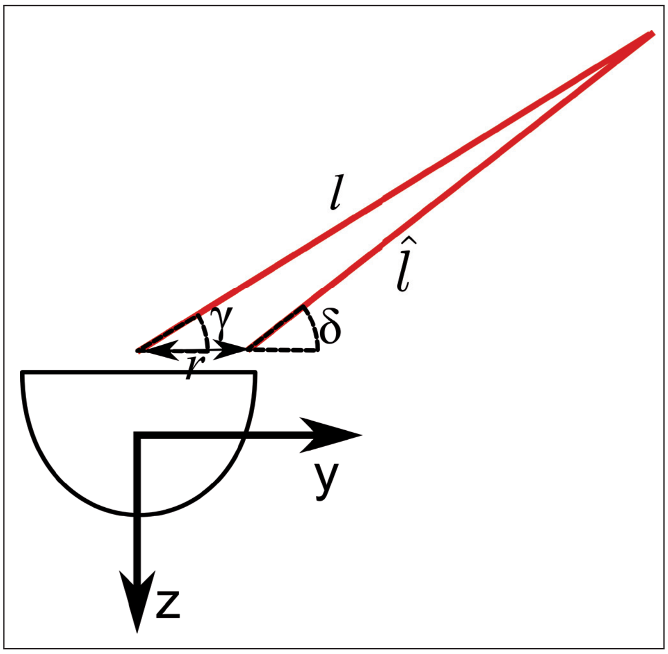

Figure 8: Correction of the hawser force due to action of the Carrousel system

All simulations were carried out with an early version of the hull depicted as ship model no 8026, the particulars of which are summarised in *Table 1*.

Overall length	L_{oA}	30.1 m
Length between perpendiculars	L_{PP}	27.5 m
Breadth max.	B	11.4 m
Draught	T	5.4 m
Displacement	∇	672 m^3

Table 1: Particulars of Ship 8026; RAVE with Carrousel system

The objective of the simulator study was to show the effects of the Carrousel system on a RAVE tug. Three experienced tug captains from Multraship performed up to 50 well-documented simulator runs. The following parameters were varied for the trials:

- Carrousel position (centre, -1.4m aft, 1.6m forward);
- Working mode as stern and bow tug as well as general manoeuvring trials with the tug alone;
- Active and passive trials;
- Manoeuvring trials up to 13 knots;
- Different VSP power and rev/min settings.

Upon completion of the manoeuvring trials, the following results and observations were recorded:

Stern tug

As a stern tug, the Carrousel-RAVE is easy to control. During a change of position, eg from braking to steering of the assisted ship, very high dynamic hawser forces of more than 200 tonnes could be generated. These high dynamic forces could be used in a so-called kite style braking, because compared to other indirect operating tugs the accelerations of this manoeuvre are very well controlled. The X/Y logic of the VSP allows a fast and stepless thrust allocation and is vital for the success of this manoeuvre.

Bow tug

The simulation run as a bow tug indicated that the Carrousel-RAVE tug offers a much higher potential compared to other tug types in this position. It is perfectly feasible to operate it at 10 knots and provide high towing forces. This is possible because the tug can sail in an indirect steering and braking position as a bow tug. The test team succeeded in finding ways of steering that allowed control of the tug's position and heading in this mode. Numerous tests were performed to swing from port to starboard side and vice versa at speeds varying from 6 to 11 knots. This manoeuvre was performed successfully with tension and also slack hawser line.

Carrousel position

For any tug the connection point of the hawser is crucial for the manoeuvrability of the tug with tension on the hawser. In general, a tug should avoid any situation where it is unable to change position or lower the hawser tension if required. This is a direct result of controlling the two biggest risks for every tug: excessive heel due to extreme hawser forces in an unfavourable direction, and collision with the assisted ship. Furthermore, it is necessary that (stern) tugs with propulsion failures enter a stable and safe position where they do not impose a risk for the assisted vessel by exerting uncontrolled steering forces.

Although the risk of capsizing is significantly reduced for a Carrousel tug, the other criteria still apply. Therefore different positions of the Carrousel were considered to ensure 'fail-safe' operation in all modes.

Obviously, the hydrostatic and hydrodynamic characteristics of the ship hull and the type, power and position of the propulsion system have a major influence on the manoeuvrability and safety of the tug. As such, the Carrousel position must always be specified in conjunction with these attributes. In the simulations it was shown that perfect handling of the stern tug braking operations occurred when the Carrousel system centre was approximately above the centre of lateral resistance (CLR) of the hull. The precise VSP force allocation according to its X/Y logic and the Carrousel system are working perfectly together and guarantee a safe tug operation.

Summary of the Carrousel-RAVE simulations

The handling and performance of the Carrousel-RAVE tug proved to be highly convincing. Especially when working as a bow tug, the simulator runs revealed that the Carrousel concept offers huge benefits in performance and safety. The simulations also demonstrated that the longitudinal position of the Carrousel system has a big influence and must therefore be chosen with care. The highly experienced tug captains involved in the simulations rated the handling of the tug as very good.

HULL FORM DEVELOPMENT AND OPTIMISATION

The hull design is a major part of any tug design, with the main goal of being effective in every design condition and operational mode. For the Carrousel-RAVE tug the requirements for performance included:

- Achievement of maximum possible free sailing speed (with minimum requirement of 14 knots);
- Capability to be safely towed at high speeds for escort and assistance operations of high speed vessels such as container ships, thus reducing or eliminating the need for the escorted ship to slow down;
- Excellent manoeuvrability in confined spaces;
- Ability to move under control and apply force in any direction;
- Highest standard of safety;
- Sufficient stability in any mode;
- Directional stability;
- International gross tonnage measurement to be under 500gt.

The general idea of the hull is not absolutely new. It is a result of Robert Allan Ltd VSP-propelled escort tug development including such tugs as ***Ajax***, ***Velox***, ***Svesia***, and others. Well proven hull components such as sponsons and the double-ended configuration have been previously used to great effect. The sponson arrangement reduces roll motions and improves stability when the tug is heeling under the influence of towline forces. At the same time, the tug is relatively narrow at the waterline level, thus benefitting from lower hull resistance. The RAVE configuration permits operation in any direction and the double-ended hull is the best solution that maximises operational speed when moving forward or aft.

The hull shape was selected and refined taking into account: tug weight; general arrangement; propeller and main machinery arrangement; towing/Carrousel system arrangement; stability requirements (particularly in escort conditions); and operational limitations of draft and length. A computational fluid dynamics (CFD) analysis was carried out for initial hull form optimisation. In particular, the resistance of five hull form variations was determined at 14 knots in an effort to minimise resistance and maximise speed. This included assessing the impact on resistance of a bulbous bow and various stern configurations such as horizontal base plates and a vertical flat transom.

The tugboat hull was configured to be towed by an escorted vessel at high speeds. Although the tug cannot achieve such high speeds under its own power, the RAVE configuration and hull form offers the capability for the tug to be safely towed at these high speeds. For preliminary purposes CFD simulations were carried out to determine the hull resistance at speeds of 16 and 18 knots. Streamlines for the alignment of potential bilge keel installation and their effect on resistance were also assessed by CFD.

Figure 9 illustrates the five candidate hulls analysed. The base case hull form had a fine stern and a bulbous bow (Hull No 1). Converting the aft end to a bulbous stern (Hull No 2) increased the bare hull resistance by 20 per cent. Replacing the bulbous bow with a conventional bow and refining the stern (Hull No 3) lowered hull resistance by 3.4 per cent relative to the base case. A flat horizontal plate added to the stern at baseline level in an effort to reduce resistance actually had the opposite effect by causing an area of separated flow and increasing resistance by 22 per cent.

Adding bilge keels reasonably well aligned with the streamlines increased hull resistance by 4.5 per cent. Hull No 4 was the same as Hull No 3 but had a bulbous bow rather than a conventional bow. A bulbous bow did not help in resistance reduction as the hull resistance increased by 4 per cent. A vertical flat transom added to the lower part of the stern (Hull No 5) for improvement of directional stability by reducing vortex shedding increased hull resistance by 3.4 per cent.

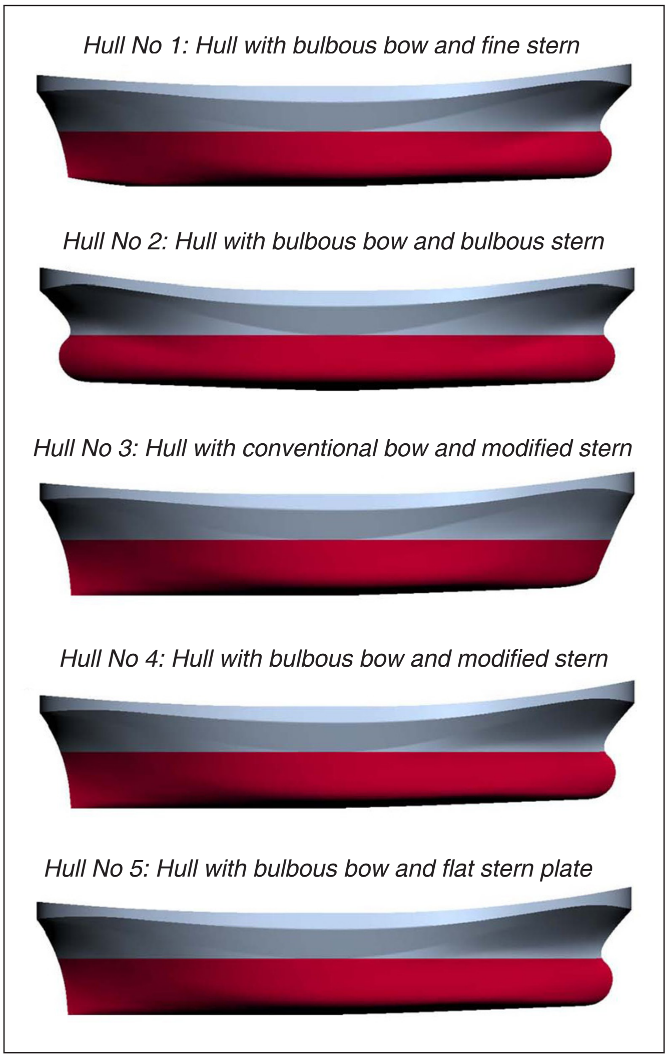

Figure 9: Hull profiles

Hull No	Description	Friction (knots)	Residuary (knots)	Total (knots)	Relative (per cent)
1	Hull with Bulbous Bow and Fine Stern	22.4	200.3	223	0.0
2	Hull with Bulbous Bow and Bulbous Stern	22.9	245.6	269	+20.0
3	Hull with Conventional Bow and Modified Stern	22.3	192.9	215	-3.4
4	Hull with Bulbous Bow and Modified Stern	22.2	209.4	232	+4.0
5	Hull with Bulbous Bow and Flat Stern Plate	22.4	217.0	239	+7.5

Table 2: Hull resistance calculation results at 14 knots

Table 2 lists the results of the CFD analysis for a speed of 14 knots. For reference, the towed resistance of the tug at 18 knots is estimated at 110 tonnes, which is 400 per cent greater than that estimated at 14 knots. Hull No 3 achieved the lowest resistance of the five candidate hulls and was selected for model testing and further development. Directional stability and hull appendages arrangement assessment was also left for the model test programme.

The effect of appendages on manoeuvrability, resistance, and tug escort performance was initially unknown because of the unique tug configuration. The following appendages where considered:

- Skeg/fin as a device for directional stability improvement and increasing indirect escort performance;
- Bilge keels for reducing motions and also for increasing indirect steering forces;
- Horizontal bottom plate, typically installed at the bottom of skeg;

CFD simulations showed the bottom plate installation had a negative effect on resistance so this appendage type was eliminated. Installation of a small skeg/fin, its size and location, and installation of bilge keels were left for optimisation during model tests.

BOLLARD PULL OPTIMISATION BY CFD

The RAVE tug has, in contrast to a traditional Voith Water Tractor, a considerable interaction between the forward and aft VSP due to the wake of the forward propeller. The interaction effect of two VSPs has already been studied in a comprehensive experimental R&D project for double-ended ferries with Voith Schneider Propellers[5]. There, the wake fraction and thrust deduction due to the interaction of bow and aft VSP were measured. The optimisation of pitch direction for VSP-driven vessels is a standard procedure for ferries with bow and stern VSPs, as well as twin screw vessels (eg tugs, OSVs, workboats, etc) and is normally done by model testing.

Because the *Carrousel-RAVE* is a new ship concept, a CFD study was carried out to find the effect on bollard pull of different pitch directions for each VSP. The CFD code COMET was used to solve the RANS accordingly.

A comparison of the traditional Voith Water Tractor (VWT) and the RAVE tug can be made by juxtaposing the isokinetic surfaces of the VSP wake of the VWT and the RAVE. *Figure 10* shows the situation for a traditional VWT.

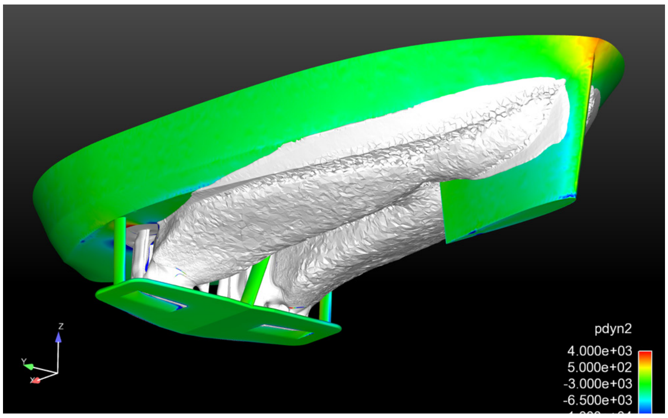

Figure 10: Isokinetic surfaces of the wake field of a Voith Water Tractor

Obviously there is only limited interaction between the two thrusters, and the wake is clearly separated on both sides of the fin. Conversely, for the RAVE concept there is a strong interaction, which is shown in *Figure 11*. The task was to find the optimum pitch direction of the bow and stern VSPs.

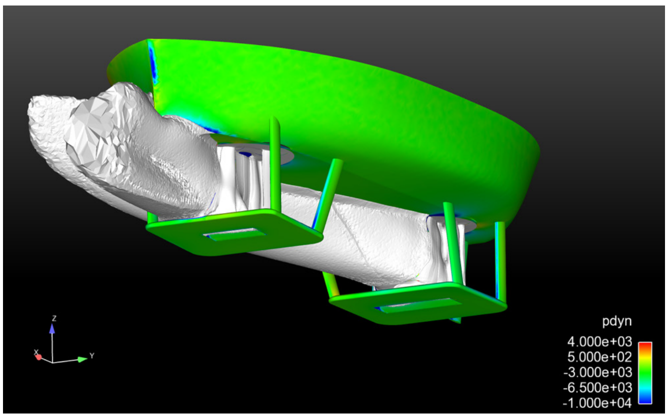

Figure 11: Isokinetic surfaces of the wake field of a RAVE tug

This pitch optimisation led to an optimum configuration where the bollard pull of the RAVE tug is in the range of the VWT, even slightly higher, as shown in *Figure 12*.

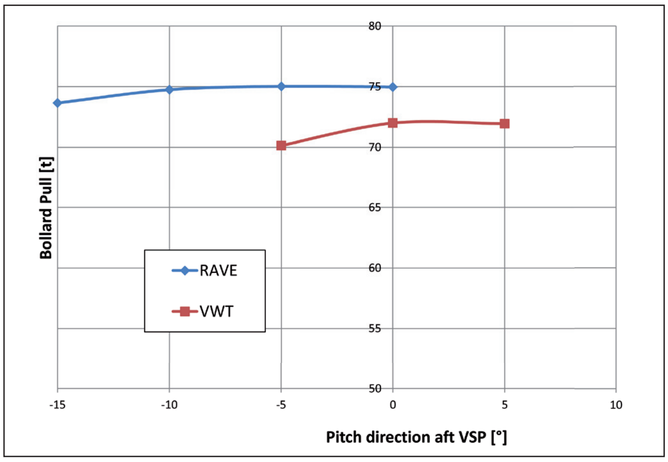

Figure 12: Bollard pull as a function of the pitch direction of the aft VSP (2 VSP 32 @ 2,600 kW)

The optimisations were also done for transverse bollard pull as shown in *Figure 13*. Here the RAVE concept offers the advantage that the interaction of both VSPs, as known for the VWT, does not exist.

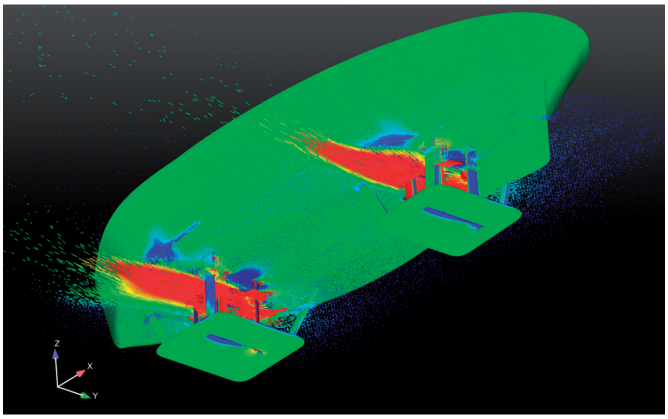

Figure 13: Pressure distribution and velocity field for transverse bollard pull

On the other hand, the guard of the RAVE is shorter. Considering the shorter guards and the different thruster interaction of the RAVE, the transverse bollard pull has the same magnitude as the longitudinal bollard pull. *Figure 14* shows a CFD result.

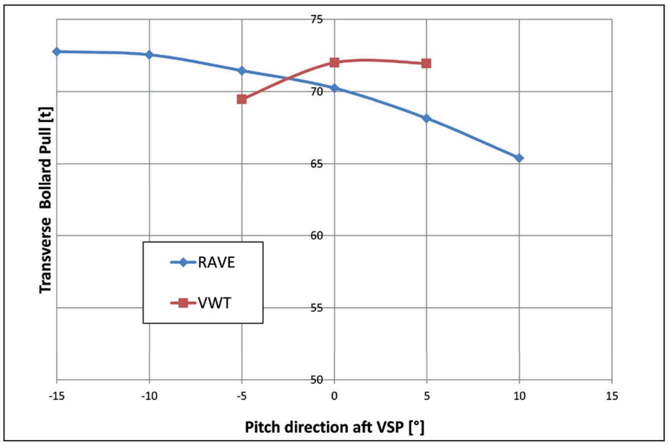

Figure 14: Transverse bollard pull as a function of the pitch direction of the aft VSP (2 VSP 32 @ 2,600 kW)

The long lever of both VSPs of the RAVE relative to each other results in the ability to create very high side forces without an undesired associated yaw moment, as well as a high side stepping speed.

MODEL TESTS

Model and model tests programme

Extensive model tests were performed at Vienna Model Basin Ltd (VMB) and co-ordinated by Alan Reynolds, president of Offshore Research Ltd (ORL) of Vancouver – one of the most experienced experts in the model testing industry. The main goals of the tests were to optimise the hull and appendage configuration for escorting and other tug operations, and to observe and determine the actual performance of the Carrousel-RAVE tug in calm water and in waves.

The model test programme was extensive and included the following:

- Self-propulsion ahead and astern in calm water and in waves;
- Side stepping;
- Escort operations in calm water and in waves;
- Towing at variable speeds including high speeds above 15 knots;
- Direct and indirect transverse arrest operations;
- Drop out conditions (with 1 and 2 engines off line);
- Cross-over operations in calm water and in waves;
- Combined arrest operations;
- Zig-zag operations;
- Resistance tests for bare hull and appended hull.

Most tests were performed with the model being self-propelled and operated by an experienced Multraship tug master. The master's involvement and feedback were key components and provided valuable insight into the handling of the tug. Feedback from the master after gaining experience with the model in multiple operational scenarios confirmed that it is easy to learn to handle and simple to control the RAVE concept.

The model was manufactured at a 1:16 scale *(Figure 15).* It was equipped with two propeller guards, two potential fin sizes (tested at both the bow and stern),

Figure 15: Carrousel-RAVE model

removable bilge keels, two transom shapes with removable parts, a Carrousel system which could be relocated along the centreline of the tug, and bow and stern towing/escort pins.

The hull model was driven by two model sized VSPs, enabling propulsion and escort tests to be carried out. For the escort and manoeuvring tests steerable VSPs were used, while for the self-propulsion and bollard pull tests the standard VSP model drives were fitted.

Optimisation of appendage arrangement and Carrousel position

With a focus on tug safety and controllability, ten different model configurations were tested and their escort performance assessed for the following operations:

- indirect steering and braking;
- cross-over and zig-zag manoeuvres;
- direct braking at speed;
- transverse and indirect transverse arrest.

Based on results of the above trials, the final hull and appendage configuration was selected. The main alterations were:

- bilge keels were removed;
- stern optional flat transom was eliminated from further consideration;
- fin moved from forward to aft location, and fin optimal area determined;
- Carrousel system optimum longitudinal position determined.

Initially the Carrousel was centred at amidships, equidistant between the VSP units and between the foremost and aftmost points of the vessel. In this configuration it was observed that the vessel was in an equilibrium position when in transverse arrest mode, but there was no additional thrust left to manoeuvre the tug out of the position. At speeds of more than 10 knots the braking force during transverse arrest is quite high and for this size of tug can be dangerous. To rectify this situation several tests were conducted with the Carrousel moved forward of amidships by different distances.

The optimal Carrousel position was found to be 1.65m forward of amidships. With this configuration, as tug speed increases, the tug has a tendency for the bow to turn towards the direction of sailing, reducing braking forces and hawser tension. Furthermore, the Multraship tug master confirmed that the final configuration, with Carrousel moved forward and with compact stern fin, was very easy to control in both calm water and head seas. This arrangement developed all the required steering, braking and towing forces when operating as either a stern or bow tug *(Figures 16 and 17)*.

Model test results and conclusions

The main results and conclusions of the model tests were:

- model configuration with the Carrousel shifted forward, compact stern fin and without flat transom or bilge keels was the optimum arrangement for escort operations;

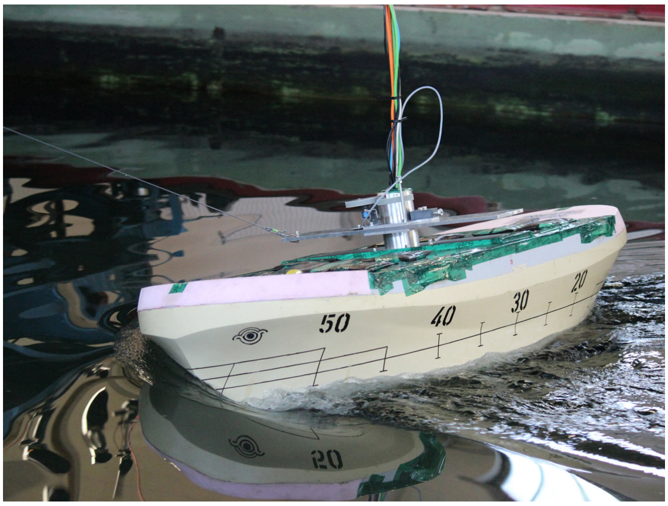

Figure 16: Escort tests

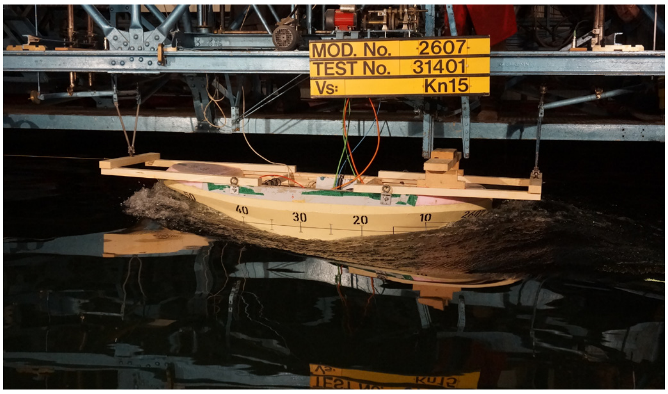

Figure 17: Resistance tests

- the final configuration is directionally stable and easy to control in calm water and in head seas;
- steering and braking forces up to 160-165 tonnes and towing forces up to 70 tonnes could be generated when operating as stern or bow tug;
- cross-over manoeuvres could be performed in less than 28 seconds in calm water and in waves;
- a side stepping speed of about 7 knots was achieved;
- the tug was shown to be failsafe with and without forward or aft VSP power;
- with an available total power of 5,300kW a speed of 14.1 knots ahead and 13.6 knots astern could be achieved in calm water;
- in 2.5m head seas a speed of 12 knots could be achieved;
- model tests showed that the tug can perform:
  – escort operations using the Carrousel at speeds up to 10 knots;
  – escort operations using bow escort pins at speeds up to 10 knots;
  – be towed by escorted vessel with maximum speed up to 16 knots and capable of applying emergency braking force by positioning in indirect transverse arrest mode;
- Model tests show that tug performs well and has good sea keeping in irregular waves with significant height up to 2.5m.

Captain experience during simulator and model tests

As already discussed, several professional and experienced tug captains have tested the performance, controllability, and sea-keeping of the Carrousel-RAVE tug in both the Voith simulator and during model tests. In the Voith simulator, two experienced tug captains tested the tug's performance and compared differences in layout. Both captains were experienced in sailing on various tug types, including ASD, azimuth tractors, VWTs and conventional tugs with twin screw shaft propellers or a combination of a single screw shaft propeller with an azimuth bow propeller (combi-tug). Both men picked up the concept of steering two VSPs in in-line configuration remarkably quickly; within half an hour to one hour both captains had full control and confidence. After running simulator tests for two full days, the captains concluded that the tug's controllability is very good and the dynamic performance meets expectations.

One tug captain was also present during the extensive 12 day model testing programme previously described. The VSP units were remote controlled and again it took this tug captain approximately one hour to give the feedback that he had the tug fully in control. Based on both the qualitative feedback from the captain and the more quantitative test results, the best arrangement was selected and tested extensively. Both the static and dynamic performance met the owner's expectations and the general judgement of the captain was that the controllability of the tug was excellent. At low speeds he was capable of turning the tug on the spot, and do side-stepping with speeds of 7+ knots. At higher speeds he was capable of utilising the VSP units to control the tug's heading and decrease and increase towline forces on request.

While the principle of a Carrousel-RAVE tug is to use the hull resistance and hydrodynamics to generate the towline forces, it must be said that the captain appreciated the additional advantage of one VSP unit forward and one VSP unit aft of the Carrousel system, which enabled the captain to increase or decrease towline forces even further by using the VSP thrust force in the same or in the opposite direction as the towline. He could sail along and so get the tension of the towline, or decide to use the VSPs to increase towline pull. Since both VSP units are on the opposite side of the Carrousel this does not alter the tug's heading.

FINAL DESIGN SOLUTION

Main particulars

Based on the results and knowledge gained from the Voith CFD and simulator training, the model test results, and taking into account all owner, class and flag state requirements, the final design configuration for the first Carrousel-RAVE tug was determined. The size of the hull is limited by both an international gross tonnage constraint and by the maximum required steering and braking forces. With a larger hull these forces would increase even further and exceed the equipment rated loads for virtually all types of vessels that require escorting. A longer hull would also drive up the size of the winch and Carrousel system, which would necessitate a wider beam, thereby exceeding the 500gt requirement. For this design especially, all components are quite interconnected.

Hull shape is designed for double ended operation but optimised for sailing ahead at maximum speed. The bow and stern are not symmetric, but the performance of the aft end is only slightly lower than that of the forward end at higher speeds. The final design particulars are:

Length overall: 31.9m

Beam overall: 13.2m

Depth, least moulded: 5.4m

Crew capacity: 6 people

Power: 2 x 2,650kW

VSP unit: 2 x 32R5EC/250-2

International tonnage: < 500gt

Class notation: BV1 ✠ Hull, ✠ Machinery, Escort Tug, Unrestricted Navigation, AUT-UMS, Fire-Fighting Vessel Class 1 with Waterspray

A rendering of the tug is shown in *Figure 18*.

Figure 18: Perspective rendering of Carrousel-RAVE tug

Towing arrangement and equipment

The Carrousel-RAVE tug has numerous towing arrangement options enabling a wide range of operations. Which system is utilised at any given point is up to the discretion of the master, depending on the area and type of operation, weather conditions, etc. The available modes are:

- towing operation using the Carrousel winch;
- towing operation using the Carrousel winch in combination with the aft tow pins;
- towing operation using the tow hook;
- towing operation using the tow hook in combination with the aft tow pins;
- escort operation using the Carrousel winch;
- escort operation using the Carrousel winch in combination with the bow escort pins.

Towing or escorting from the Carrousel winch
Capable of 360-degree rotation, the Carrousel winch can be used for both traditional towing and escort operations with a high level of manoeuvrability. The winch uses its own towline and due to its rotational capability can be used equally as effectively when sailing ahead or astern; steering when sailing astern will differ very slightly from when sailing ahead because, as described earlier, the centre of the Carrousel is biased towards the forward VSP unit.

The Carrousel ring is installed on a raised portion of the main deck, the top of which is at the same height as the top of the bulwarks. The bulwark top is flush for the entire length of the vessel and has a round stainless-steel pipe at the top to reduce wear on the towline. The remainder of the deck equipment is installed as close to the bulwarks as possible, with height below the bulwark top, to reduce the possibility of the towline snagging. Additional safety guard rails are installed around partially exposed deck equipment to guide the towline over the equipment when going from a slack to taut position.

Escort operations using Carrousel winch and bow escort pins
The Carrousel winch can be used either independently for escort operations or in combination with a set of heavy duty escort towpins installed at the bow. The pins are retractable and, when not in use, are flush with the top of the bulwarks. When in use, the top of the pins connect on centreline to constrain the line, and well-rounded corners on the fore end of the pins prevent line wear.

Towing operations using Carrousel winch and stern tow pins
When undertaking towing operations the Carrousel winch can again be used independently or with the towline guided through an optional deck-mounted tow pin unit aft. The tow pins are angled and incorporate rollers; when not in use the rollers are retracted and the top of the unit is flush with the bulwarks. This would be an attractive arrangement for long distance line towing, where not much change in direction is required and the winch does not need to rotate.

Towing operations using tow hook
An optional, 70-tonne SWL tow hook is installed under the Carrousel winch. The hook can be used with or without the aft tow pins, and would accept a separate towline. It is also installed as a back-up in case the winch is out of service or cannot be used for any reason. Installed neatly under the Carrousel winch, it can also be rotated to the side for storage.

Fender arrangement
The sides of the tug, including the sides of the raised portion supporting the Carrousel ring, are enveloped by 300mm deep D fenders. The bow and stern both have 300mm deep, 480mm wide ‘W’-style fenders. Additionally, the stern bulwarks support an 800mm OD cylindrical fender for pushing operations. The cylindrical fender can compress at least 200mm before the W fender below it will engage, and the bulwarks are specifically designed to allow compression of the cylindrical fender and not restrain it, reducing wear and tear.

Machinery arrangement
The unique in-line arrangement of the VSP units for the RAVE configuration does not allow for the main engines driving the units to be installed longitudinally in the vessel. In order to allow adequate space between the engines for access in the engine room, the shaft lines are rotated outboard from the centreline, with the port engine driving the aft VSP unit and the starboard engine driving the forward unit; the engines overlap at amidships. To meet FiFi1 notation requirements each engine also drives a fi-fi pump off its PTO end. Steps are provided over the shaft line near the input to each VSP unit to enable access to the outboard side of the engine room along the length of each shaft line.

Main engine and gen set silencers are installed horizontally in the engine room deckhead under the Carrousel deck, with only the exhaust pipes running through the deckhouse to the open bridge deck. This was done in order to reduce the size of the deckhouse to fit inside the Carrousel ring, and optimise and maximise the accommodation space above deck.

Main engine cooling is provided by rack coolers installed in dedicated bays forming part of the double bottom structure. The rack cooler installation was chosen instead of box coolers since heel angles can get quite high during escort operations with the Carrousel winch. If box coolers were installed on the vessel sides there is a very real risk that the box cooler bays would be partially out of the water on one side during these operations. Gen set and auxiliary equipment are cooled by dedicated Pleat coolers. Three equal, small generator sets will be installed onboard. In low load conditions, such as in harbour, only one will be used. A second gen set will come on-line for higher load, regular operating conditions. The third gen set will be used for standby and system redundancy. All three are capable of running together in parallel for full load sharing.

Where possible, tank vents are installed inside the Carrousel ring along the side of the deckhouse so there is no interference with winch operations. In this case, the vents are raised quite high in order to avoid any water entering either from green water or operations with high heel angles. However, space in between the deckhouse and Carrousel ring is quite limited and for tanks at the ends of the vessel it is not practical to run piping under the Carrousel deck. These vents are installed under the bulwarks, if possible close to the vessel centreline, and are fitted with automatic closing devices.

Accommodation arrangement
In order to avoid interference with the winch and keep the crew safe during towing or escort operations the

deckhouse and wheelhouse on the tug are installed inside the inner ring of the Carrousel system. The sole of the deckhouse is on the raised portion of the Carrousel inner ring housing. To maximise usable internal space, the deckhouse footprint is circular, with its centre coincident with the centre of rotation of the winch. Steel-to-steel, the deckhouse is 2.75m in height, and features generous chamfers to the bridge deck to increase visibility of the winch and main deck from the wheelhouse. The two exits/entrances in the house are perpendicular to each other and linked by an L-shaped corridor, with one exiting to the aft deck and the second to the port side of the vessel. This ensures that, regardless of the location of the winch at any given time, there is at least one exit that is not blocked.

The master's and chief engineer's cabins are located on the forward side of the deckhouse with a shared en suite washroom and spacious floor area of approximately 9m^2 each. A galley and mess with seating for eight are on the aft side of the house. A small washroom and change room are also included for crew coming inside from the working deck or down from the wheelhouse. Internal access to the wheelhouse is provided via a spiral staircase near the galley, and access to the lower accommodation space and engine rooms is down a staircase on the starboard side.

The lower accommodation compartment is located at the bow of the vessel under the main deck. The compartment houses an HVAC room, galley stores, 2 x 2 crew cabins, a shared washroom and laundry facilities. The cabins each have a floor area of 7.6m^2. Depending on the intended type and area of operation of the vessel and the required number of crew, the internal arrangement can be reconfigured in several different ways.

Wheelhouse arrangement and VSP control arrangement

An absolute must to ensure the safety of the Carrousel-RAVE tug is 360-degree visibility. Numerous design features were implemented to increase visibility, while still maintaining visual aesthetics:

- large side windows cover the perimeter of the house, minimising blind spots;
- the wheelhouse geometry is completely symmetric forward and aft so there is no difference when operating ahead or astern;
- the forward and aft faces of the house are sloped at approximately 20 degrees from the vertical direction to reduce glare, while ensuring adequate sightlines to the winch and main deck below;
- the wheelhouse top is flat (horizontal) to maximise the size of the upper side windows, increasing overhead visibility over the side;
- the wheelhouse top structure has been optimised for increased visibility through the upper windows from any operator position with the use of low profile structural members;
- the wheelhouse sole is raised vertically from the bridge deck, increasing visibility of the winch in any position;
- as mentioned earlier, generous tumble-home on the perimeter of the deckhouse enables good visibility of the winch and main deck.

Internally, the console arrangement had to be unique in order to address the following key design features:

- the vessel is designed to be fully double-ended, and can perform all necessary manoeuvres both when going ahead and astern;
- the VSP units in RAVE configuration are positioned longitudinally inline instead of transversely side by side, meaning each unit must be controlled independently. Individual joystick controls are much better suited for this application than the traditional common wheel;
- since the Carrousel winch can rotate freely the towline can often be in an orientation where the vessel is basically operating sideways; the operator must be able to face the direction of travel and maintain visibility with the winch at all times.

Several different console and VSP control arrangements were presented and discussed with Multraship. The final arrangement will feature a four-console arrangement, with four joysticks installed. As in Z-drive operations, each unit will be controlled independently. The details of the final control system are still under development in order to ensure the final arrangement is intuitive for all operators and for all possible operations.

SAFETY MEASURES OF THE DESIGN

Safety is of upmost importance in the operation of the Carrousel-RAVE tug, and a huge design effort has gone into enhancing the safety of the vessel and protecting against potential flooding from grounding or collisions. The following measures have been implemented:

Protection in case of grounding, collision and flooding

Complete fender system

The fender arrangement has been described under 'Towing arrangement and equipment'.

Propeller guard and fin design

Each VSP unit has an independent propeller guard that extends 2.85m below the hull bottom. The aft guard is attached to the stern fin, which is equally deep. The structure of each guard was optimised and checked using finite element techniques to sustain very high impact loads: 500 tonnes longitudinally, 500 tonnes vertically, and 250 tonnes transversely. That means that both propeller guards together can resist the impact of a grounding force up to 1,000 tonnes longitudinally (14 times more than bollard pull), up to 500 tonnes transversely (seven times more than bollard pull), and up to 1,000 tonnes vertically. Given the fore and aft arrangement of the guards, this provides protection of the hull bottom along the entire length of the engine room.

Since the attachment points of the guards to the hull are through the struts, it is conceivable that very high impact loads could compromise the integrity of the hull at the strut intersections. Although at the time of writing the authors are unaware of any instances of this type of damage occurring in practice, and the finite element analysis showed no weak spots around these areas, additional protection was designed inside the hull in the event this type of damage does occur.

Aft and forward collision bulkheads and double sides in engine room

Since the vessel is fully double-ended, both the aft and forepeak bulkheads are located and designed according to collision regulation requirements. The engine room is protected from side damage by longitudinal bulkheads which comprise the vessel's eight fuel tanks. The hull design inherently provides bilge protection from side damage since the sides flare outwards (ie not vertical sides). For reference, the bilge area is a minimum of 1m inboard from the deck edge at amidships and up to 1.7-2.5m inboard in way of the propeller guards.

Installation of watertight compartments and deep tanks

The engine room is separated from each of the fore and aft collision bulkheads by deep void compartments and deep tanks. These spaces surround the perimeter of each VSP unit, so any bottom or side penetration aft of the aft VSP unit, forward of the forward VSP unit, and directly outboard of both units will only result in flooding of the void space or deep tank, and not access the larger engine room.

Partial double bottom construction

Installation of double bottom type structure is not possible in the entire engine room of the Carrousel-RAVE tug due to the specific arrangement of the main engines and VSP units. The VSP well flange height above the hull bottom is dictated by the height of the VSP unit mounting flange. For the 32R5 unit this dimension is lower than the SOLAS minimum required double bottom height of 760mm.

Additionally, the VSP wells are supported by deep radial girders and floors. These members are highly stressed areas and ability for easy inspection is critical. If this supporting structure would be changed to a double bottom-type construction the space in between each of these supports would be inaccessible and would require individual bilge suctions, vent and sounding pipes.

Similar arguments can be used for structure in between the two sets of engine girders, since the engines are sitting quite low in the vessel. In all other areas of the engine room, including the space between the two engines and all structure outboard of 3m off the centreline, double bottom structure is installed. BV Class has agreed with the above methodology and has granted an exemption for a partial double bottom installation for the design. *Figure 19* depicts all the different areas of the hold plan which are protected by the above mentioned devices.

Enhanced escort stability criteria

The tugboat is capable of escorting operations by two means: using the Carrousel winch or by using the bow escort pins. As the physics of the escort operations when using the Carrousel are different than the conventional operations assumed by classification societies when establishing escort stability criteria, a modified method had been proposed for confirming the stability of the vessel during escort operations. This method takes into account the much higher towline forces created by the Carrousel-RAVE combination, and the fact that the towline force does not act on the vessel centreline but at the edge of the Carrousel ring.

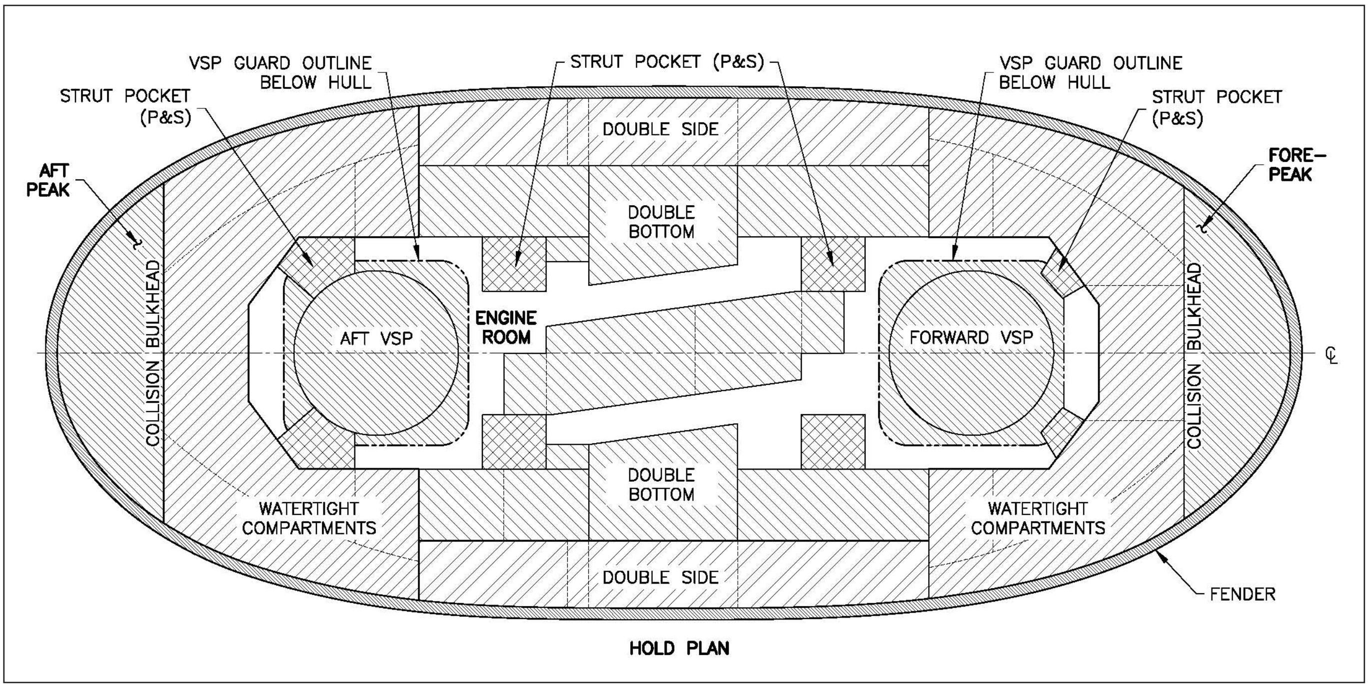

Figure 19: Plan view of protected areas for Carrousel-RAVE tug

Operational safety measures

Controllability

Model tests and Voith simulator trials showed the Carrousel-RAVE configuration to be highly controllable for any type of towing, ship-assist, or escorting operation. The in-line arrangement of the Voith units means the captain will always have a thrust lever available and be able to change the vessel's heading if a situation becomes uncomfortable. Additionally, an inherent feature of the VSP drives is that when de-pitched they do not produce any more thrust, unlike nozzled propellers which even at low power would still act as rudders. This enables the captain to quickly take-off thrust when needed. When/if this happens the model tests showed the vessel would just slowly fall in line behind the assisted vessel and maintain heading (this was analysed by simulating one and two engine drop out trials).

Visibility

As mentioned in detail under 'Wheelhouse and VSP control arrangement', several features of the wheelhouse design allow for increased visibility in all 360 degrees of operation, and constant visibility of the Carrousel winch and other deck equipment.

Escape routes

In case of emergency, at least two escape routes are available to crew from inside any compartment. To exit the lower accommodation area the primary escape is through the stairs up to the deckhouse, with the secondary means through a hatch in the laundry room on the port side. From the engine room, switchboard room or workshop, the two escapes are either through stairs on the starboard side to the deckhouse, or a port-side escape hatch to the main deck. Exit out of the deckhouse is through either of the two entrances which, as explained earlier, are arranged in an L-shape to enable one exit to always be free of obstruction by the Carrousel winch. Exits from the wheelhouse are via the port and starboard weathertight doors.

CONCLUSIONS

Development of the Carrousel-RAVE tug was not a short clear path from idea to realisation. This development included Multraship and Novatug experience of development and construction of Carrousel tugs, and 12 years of safe and successful operation of the first ever Carrousel tug – ***Multratug 12.*** It also includes results of the extensive six-year collaboration between Robert Allan Ltd and Voith during development of the RAVE tug concept including multiple model tests, simulations, research, CFD calculations, studies, etc.

This combined effort has resulted in the design of the first Carrousel-RAVE tug, a vessel offering exceptional and unique capabilities. This compact, 32m tug, under 500gt, can generate and safely apply forces during ship assist and escort operations equal to at least 1.5 times more than any other type of similar sized tugs. At speed, significant hydrodynamic forces can be generated by simply applying minimal thrust sufficient to change the tug orientation. This capability results in considerable fuel savings during operations and offers increased controllability since more thrust can always be applied to change the orientation.

The tug is designed with exceptional manoeuvrability; it can move in any direction with reaction time of a few seconds and can generate maximum thrust through 360 degrees. It can work in confined spaces such as locks and narrow canals where other type of tugs cannot be effective.

The new tug design has all the necessary attributes of standard tugs such as sufficient and comfortable accommodation, large engine room convenient for service, and sufficient capacities of consumables. The wheelhouse has 360-degree visibility and a unique console arrangement for 360-degree operation. The tug is designed with all necessary safety measures that can protect tug and crew against damage from grounding, collision, flooding and fire.

The results of all the design and development work performed to date has provided the owners and the design team with the highest degree of confidence that the Carrousel-RAVE tug represents an extremely effective new tool in ship assistance and escort.

ACKNOWLEDGEMENTS

The authors would like to sincerely thank: Robert Rodenburg, Novatug BV; Vienna Model Basin (SVA) and staff; Alan Reynolds, Offshore Research Ltd and model test co-ordinator; Hildebrand Kamerling, Henk Helmendag and Edzard Kellermann – Multraship and Voith tug masters present at Voith simulator trials and model tests; and Gijsbert de Jong, Bureau Veritas.

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