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LUNCH PRESENTATION DAY 1 SESSION

DP Advances in the USN Seabase: STLVAST Sea Trial and Completion

By Dr Greg Hughes, Oceaneering International
Dr Rick Harris, MAPC
Ir. Frans Quadvlieg, MARIN
Ir. Rink Hallmann, MARIN

Introduction

In this third and final paper the STLVAST team present an overview of our work and describe the full scale offshore trials conducted by the USN that showcased some of the potential of the Close-in Precision DP work carried out by STLVAST. Having experimented with cycloidal thrusters and wave feed forward technology, the STLVAST team prepared and executed a full scale demonstration of precision seakeeping by bringing the Mighty Servant 3 alongside a large cargo vessel. Using only DP and no lines between the ships, the MS3 maintained a position close alongside the cargo vessel. This position was safely maintained at zero knots and 3 knots ahead, in Sea State 3, for 2 hours.

STLVAST is a 3 year Science and Technology program supported by the Office of Naval Research (ONR) focused on improving Close-In Precision DP for applications in the USN's future seabase. In terms of technology development STLVAST can be divided into four 'phases':

- Cycloidal Thrusters
- Wave Feed Forward
- VTAST Sea Trial
- Heading Control

Each of these phases is described in the following sections.

Phase 1 Cycloidals

The STLVAST CIP DP investigation began with an overall assessment of how the STLVAST operational scenarios differed from those typically encountered with existing dynamically positioned vessels. A detailed discussion of this investigation is presented by Hughes et. al. [1], but in summary, several key issues were identified:

- Forward speed introduces "bank effect" hydrodynamic loads between the two vessels and increases sway/yaw coupling in the ship maneuvering dynamics
- The close separations and high sea states envisioned for STLVAST required ship positioning accuracy which was better than typically achieved with existing DP vessels.
- Forward speed decreases the lateral force producing effectiveness of conventional azimuthing or tunnel thrusters.

We thus concluded that, compared to existing DP operations, STLVAST had to contend with larger disturbances to ship motions and tighter performance requirements under conditions of reducing actuator effectiveness. The simplest conceptual approach to meeting these challenges was to find higher performance actuators and use a more aggressive tuning of the DP control system to satisfy performance requirements. "Higher performance" in this case refers to two actuator characteristics, the rate at which it can respond (bandwidth) and how much force it can generate (authority). Bandwidth is critical because a faster acting controller allows the DP feedback system to use higher controller gains and therefore provide better disturbance rejection properties without sacrificing system stability. Authority is likewise critical since even a fast responding actuator is useless unless it can generate forces which are compatible with the magnitude of the disturbances.

It is worth noting that increased controller bandwidth and feedback gains can create the need for faster acting position measurement and filtering systems (e.g. Kalman filter) as well since delays in these portions of the feedback system can also be de-stabilizing. These and related issues are discussed in more detail in Hughes et. al. [2] and in standard control texts such as Maciejowski [3]. A survey of available actuators quickly focused on Voith Schneider cycloidal propellers (VSP's) for the following reasons:

- A VSP can reverse thrust in less than 5 seconds. Typical azimuthing thrusters take closer to 10 to 30 seconds. Thus VSP's improve bandwith.
- The lateral force generated by a VSP can actually increase with forward speed. Typical azimuthing thrusters can lose as much as 75% of their lateral force generating capability at 8 knots ship speed. VSP's are also available in sizes up to 3.8 MW. Thus VSP's improve authority.

The ability of a VSP equipped MLP surrogate (the Mighty Servant 3 (MS3)) to meet STLVAST performance requirements was demonstrated at MARIN in a series of model experiments in their seakeeping and maneuvering basin (SMB) in April of 2008 and reported by Hughes et. al. [1]. Photographs of the model are shown in Figure 1.

Figure 1 – Photographs of Bow and Stern of Mighty Servant 3 Equipped with Voith Schneider Propellers

The tank test campaign considered single and two ship operation at a variety of ship speeds, separations, control tunings, sea states, and wave incidence angles. The second ship for all two ship testing was a T-AKR 310 (Watson Class) LMSR.

Figure 2 summarizes the two ship relative positioning performance of the VSP equipped MS3 as a function of ship skin-to-skin separation and ship speed. The variable plotted is the maximum deviation of the MS3 reference position (approximately midship, centerline) from its ordered position relative to the LMSR in a half hour of simulated operation. Conditions were at the top of seastate 4 and bow quartering seas with the MS3 to lee of the LMSR. For all cases the VSP's were limited to 3.8 MW power each except the one point indicated by the rainbow colored circle where the rating was increased to 8 MW at 7.5m separation and 8 knots.

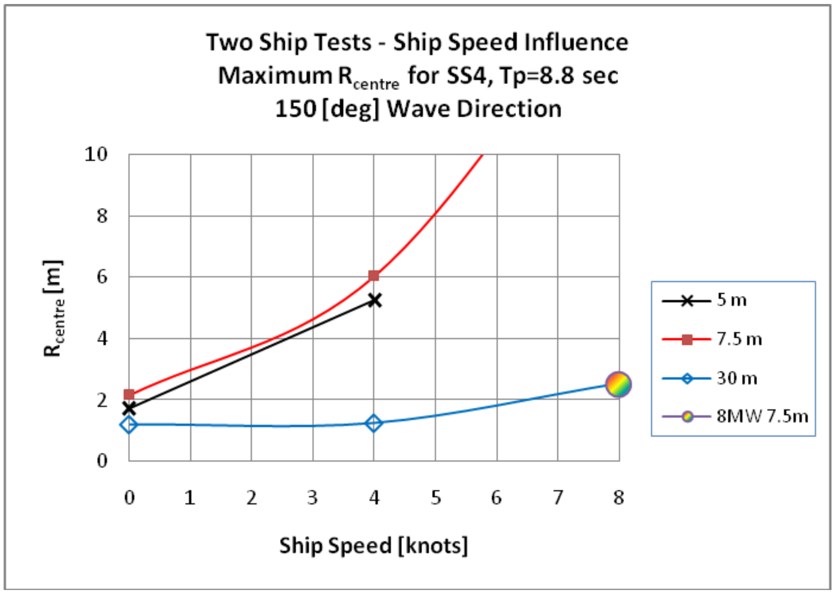

Figure 2 - Rcenter as a Function of Ship Speed

Figure 2 shows some compelling performance in seastate 4, and that tracking errors increase with ship speed, particularly at close separations. This is likely due to additional wave diffraction and scattering as well as bank effects. Increasing VSP authority to 8 MW provides extremely good performance.

Phase 2 Wave Feed Forward

A traditional DP system can be characterized as mainly a feedback system (with the exception of wind). This means that the ship starts to react on a velocity and a displacement away from the set-point. In reality, this means that the control system is an 'always-too-late' control system.

One exception is the way wind is managed by the control system. A wind meter is placed on the ship, measuring the actual wind velocity. By measuring the wind velocity, the instantaneous wind forces on the ship is calculated, and this is fed directly into the controller. This allows the system to respond earlier as there is no need to wait until the wind causes the vessel to drift away, the controller to measure this displacement, and the ship to react to this displacement. By applying this 'wind feed forward', the system would move from a always-too-late system to a 'just-in-time' system. The advantage is that it can counter the influence of a wind to the ship directly and does not require errors to accumulate. The disadvantage is that it requires an accurate estimation of the wind force in order to use the actuators properly. The measurement of the wind forces is straight forward: it requires a wind anemometer, and knowledge about the relation between wind velocity and forces and moments. The relation between wind velocity and forces and moments is generally referred to as wind coefficients, either measured in a wind tunnel or calculated by computational methods such as CFD. The application of Wind Feed Forward is well established and is a large improvement. Figure 3 shows this DP control loop.

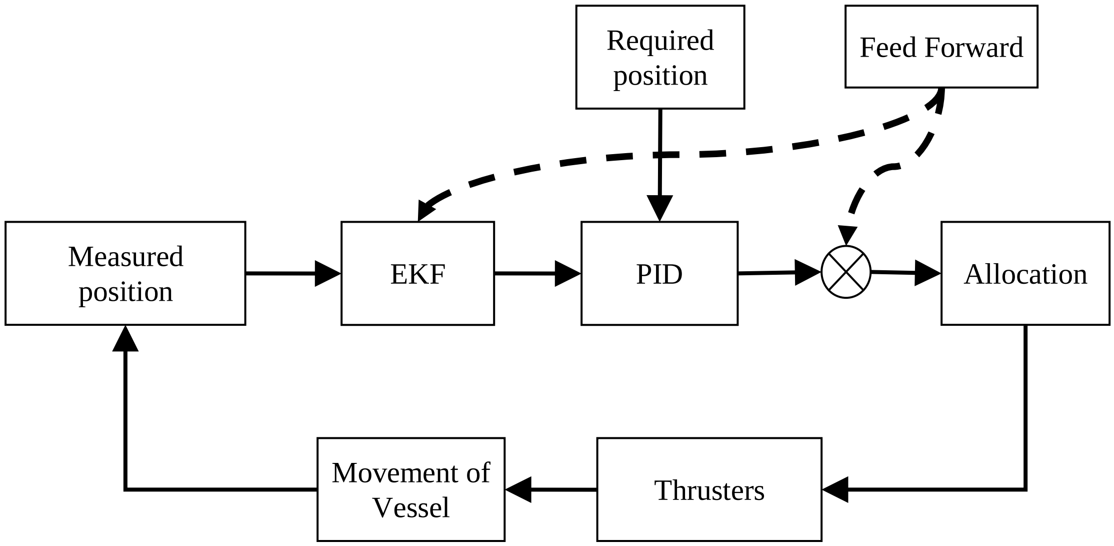

Figure 3: DP control loop with wind feed forward

Wind is one source of disturbances. A second important source of disturbance are the waves. In the second stage of STLVAST we investigated whether the disturbances due to waves could be counteracted better by using Wave Feed Forward in the same way as Wind Feed Forward. This basic idea is not new, and other researchers have elaborated this idea in the past, see Pinkster [4], Aalbers et al. [5], [6] and [7].

Waves cause two types of wave forces:

- First order wave forces, a wave frequency wave force, causing a back and fore force every time a wave passes. These forces are proportional to the wave amplitude and occur at the wave encounter frequency.
- Second order wave forces, these are proportional to the square of wave amplitude, occur at frequencies below the encounter frequency of the waves, and are non-zero mean. So, there is a mean wave drift force (an average force, roughly in the direction of the waves) and a low frequency wave force which is more related to wave groups.

The theory behind the second order wave forces is developed by Pinkster [4]. This boils down to the fact that the instantaneous wave forces are related to the instantaneous relative wave height around the ship.

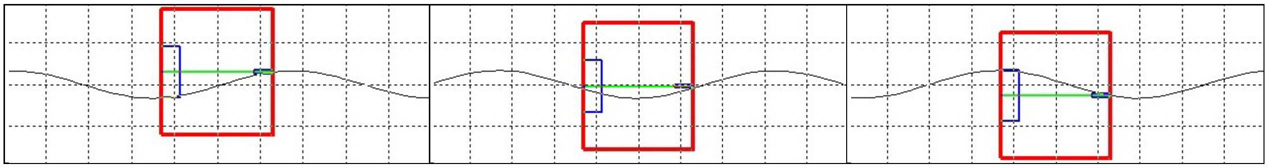

Figure 4: Difference in Wave/Hull Contact Line Near Heave resonance

Second order wave disturbances result primarily from the quadratic terms in Bernoulli's equation, the relative phasing of hull motions and incident waves, and wave diffraction. The phasing effects are dominant for wave frequencies near pitch and heave resonance while diffraction effects are dominant for higher frequency waves. Figure 4 illustrates the dramatic difference between the maximum and minimum wave/hull contact line for a heaving 2-D cylinder near heave resonance.

It is generally acknowledged that a DP system needs to cancel the second type of wave disturbance. The cancellation of the first order wave forces would require very large forces which would need to switch to the opposite direction every 6 seconds. It is impractical to counteract these first order disturbances with normal azimuthing thrusters. The focus of “wave feed forward” is hence to sense these second order wave forces, feed them ‘forward’ in the DP system and hence obtain a higher DP accuracy. A higher accuracy is achieved when the watch circle has decreased.

There are two approaches to measuring the wave forces. A first approach is that the wave forces on the ship are measured by measuring the local relative wave height. A second approach would be that the wave is measured by a wave radar. However, knowledge of a far field wave is not the same as knowledge of the instantaneous wave forces around the vessel. We therefore focused on the method of predicting the second order wave disturbances using the instantaneous relative wave height around the vessel.

Initially WFF was tested and the performance improvement recorded for a single vessel in a seaway. The MARIN test facility allowed tests to be performed in exactly the same wave trains. This enabled our team to perform a very objective comparison for the performance with wave feedforward enabled and disabled.

After having established what the correct DP settings should be for the specific ship, several tests were performed in a large variety of sea states. Sea states of interest to the project were sea state 3 and sea state 4. Figure 5 shows the performance in the target wave (wave height Hs=2.5m; peak period Tp=8.8 seconds and bow quartering waves (150°)). A significant improvement is demonstrated. This is mainly because a few large excursions are now ‘seen in advance’ and the ship reacts to them early enough to prevent a large position error.

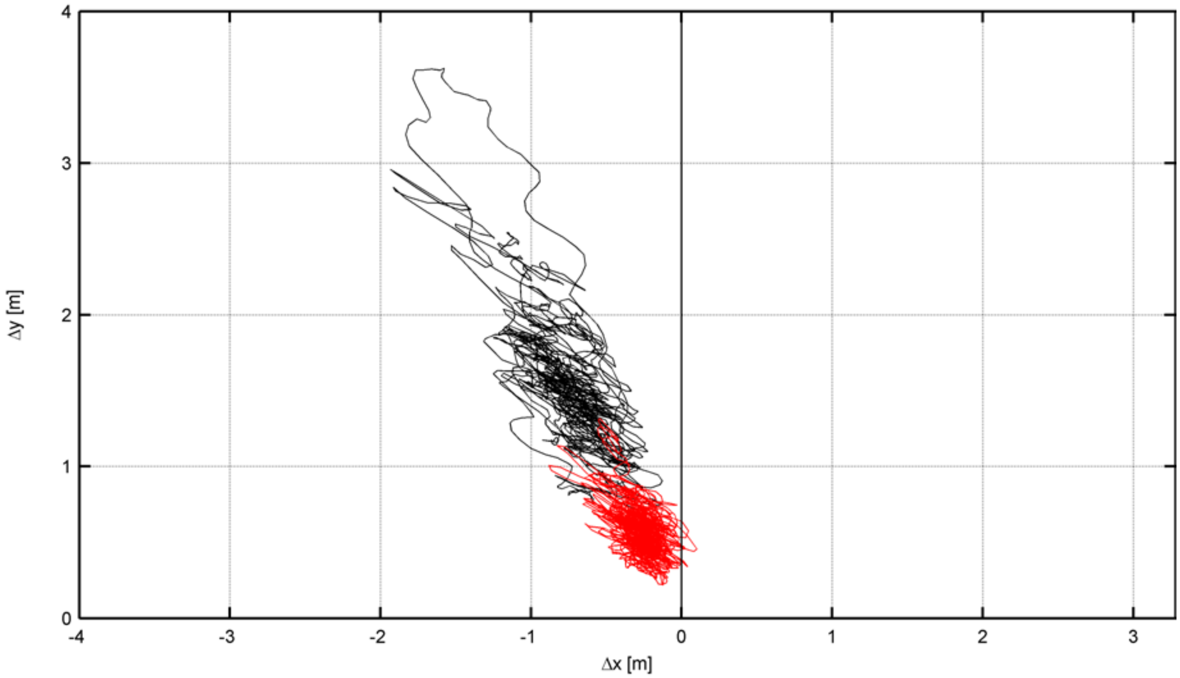

Figure 5: Footprint of trajectory of the centre of gravity, in surge and sway, of the Mighty Servant 3 in Sea State 4, bow quartering waves; WFF disabled (black line) and WFF enabled (red line)

A similar performance improvement is demonstrated in waves coming from other directions as well. This is shown in Figure 6. Wave feed forward has lead to a very significant improvement in positioning accuracy.

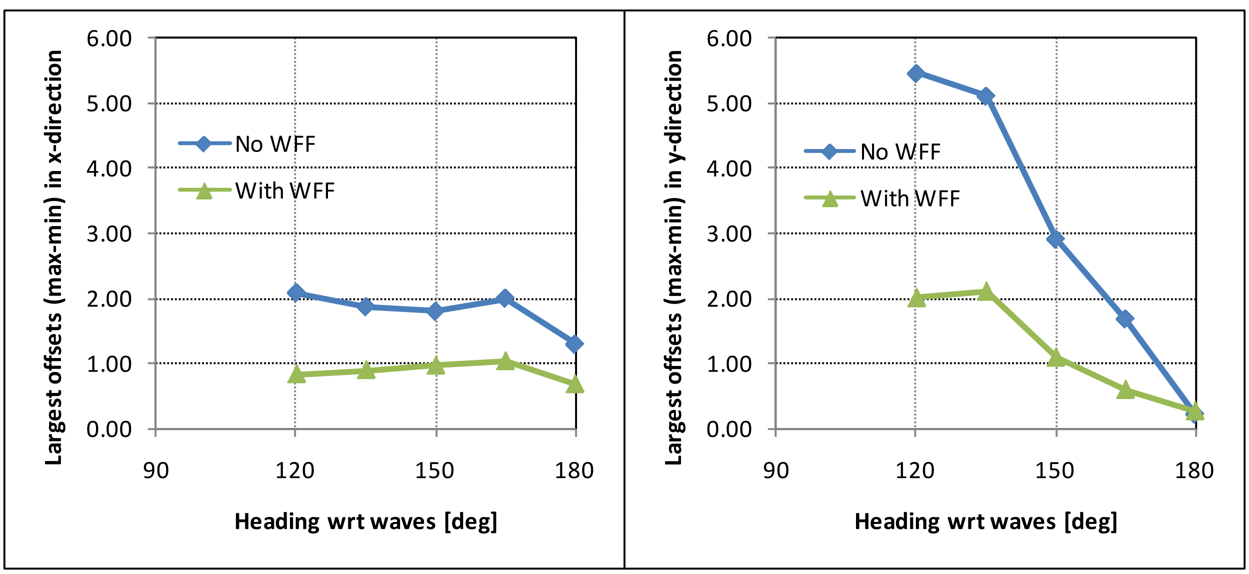

Figure 6: Improvement in watch circle (shown in surge x, and sway y) in sea state 4, for various wave directions, zero speed

When two ships are taken and relative DP is performed, a similar test approach is carried out: the performance with and without wave feedforward active is quantified in exactly the same wave trains. Figure 7 makes this comparison. When a single ship is attempting to maintain its position relative to a second vessel in a seaway, performance is only improved at some headings.

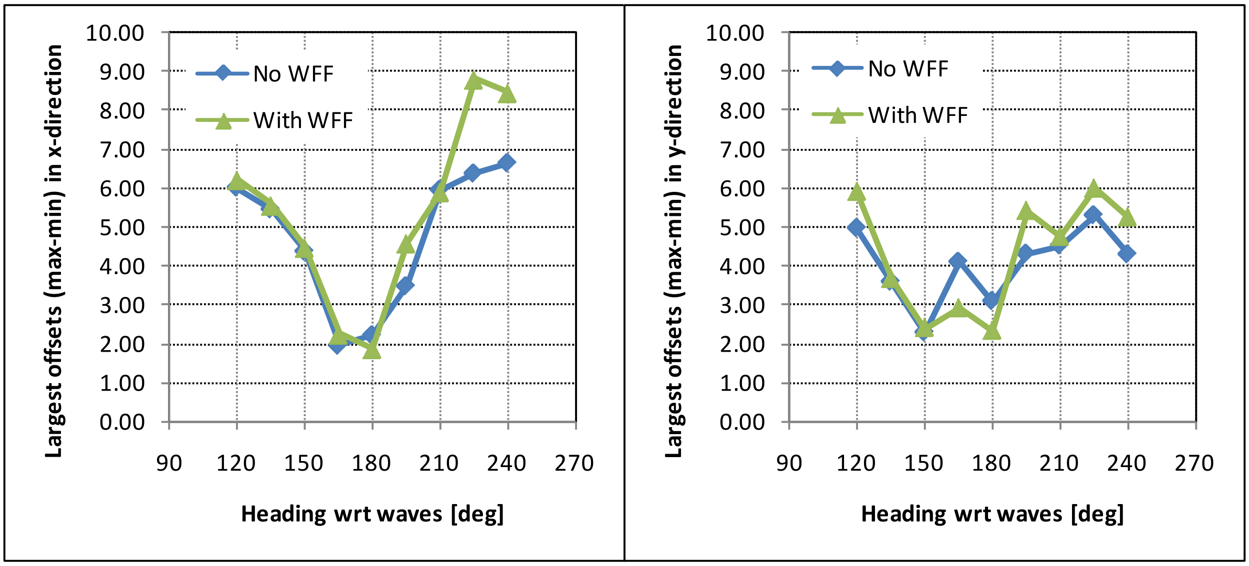

Figure 7: Comparison of maximum swept path for two ships in relative DP with and without wave feedforward

So, although the knowledge of the wave forces enables the active DP vessel to counteract wave forces and hence improve performance, the second vessel (which does not have a full DP capability or wave feedforward enabled) moves as a consequence of the waves as well. If this movement of the second vessel correlates to the wave induced movements of the MS3, it would be better, momentarily for the DP vessel to move with the wave drift rather than to counteract them. Several solutions suggest themselves to address the “tracking issue” including the development of a two body Kalman Filter. For this, the motions of the following vessel (in this case the Mighty Servant 3) should be used to predict the motions at the next time step of the second vessel. Wave feedforward proved extremely successful for a single ship, but challenges still remained as we applied it to the two ship tracking scenario.

Phase 3 VTAST Sea Trial

At the end of June 2009, with the VTAST sea trial only 6 months away ONR directed STLVAST to demonstrate Close-In DP performance at full scale:

- WFF would not be demonstrated, as results for two ship performance were mixed and modifying Kongsberg certified DP software in the time remaining would be very challenging
- Close-In performance supports the crane transfer of loads between vessels, in the absence of a TAVTS ramp

The goal of the STLVAST part of the VTAST sea trial was to bring the MS3 (outfitted with 5 portable 1.5MW Azimuthing Thrusters) close alongside the LMSR, using COTS DP, and maintain the ‘operational distance’ safely for two hours at both zero knots and at 3 to 4 knots ahead speed. All this to occur in seastate 3 but no crane transfer during the alongside period would take place as this was a trial of a DP capability. Figure 8 illustrates the ‘operational distance’ which is touching the rear fender and yawed out 2 degrees at the bow. This arrangement is selected instead of a parallel position because the MS3’s starboard thruster porch is forward of the front fender, and therefore not well protected. Even though the VTAST was a sea trial we developed a comprehensive DP Operators Manual that included Project Specific Operating Guidelines (PSOG), a step by step procedure for the experiment and an escape logic.

Bringing the MS3 and LMSR to the crane 'operational distance' (about 15' apart, just touching the fenders) required:

- Extensive testing of multiple new vessel configurations
- An improvement in Kongsberg 'follow target' code
- Upgrading and instrumentation of two 4.5 m fenders on MS3

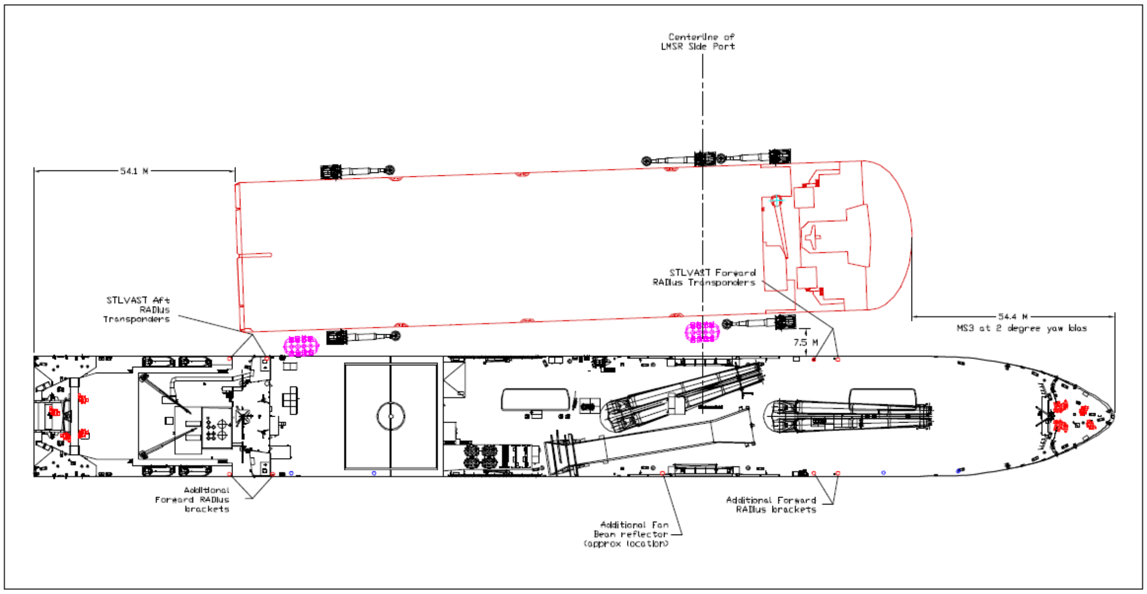

Figure 8: Plan view of the 'operational distance' used during the VTAST sea trial

All of the required equipment and software upgrades were successfully completed in time for the sea trial which began in late January 2010. The STLVAST team joined the MS3 in early February and embarked for the trial area, west of Tampa in the Gulf of Mexico. From late afternoon on Saturday 13th Feb until the evening of Sunday 14th Feb the MS3 and LMSR conducted Close-in Proximity DP tests. Saturday testing in seastate 4 allowed checking and calibration of the various relative position sensors, the vessels did not approach closer than 30m. On Sunday, in SS3, the MS3 was safely maneuvered to the 'operational distance' and safely maintained it's close proximity to the LMSR for 2 hours, at zero knots, and then the test was repeated at 3 knots ahead speed (see Figures 9 and 10). In both tests the MS3's DP system kept the relative watch circle and relative bearing between the vessels, within the previously defined PSOG limits of 2.5m and 1° yaw (bow-in). Figures 11 and 12 record the relative watch circle for the two vessels during the two hours of close proximity. The results were excellent, with the tight watch circles validating Kongsberg's improvement in the "follow target" and the skill of the C-MAR DPO's. The improvement in the watch circle seen as we moved ahead is consistent with our MARIN tank results and occurs as a result of the effective biasing of the thrusters. In the 3 knot test the five thrusters produce the ahead thrust to keep the MS3 next to the LMSR, in addition to producing the athwartship thrust to maintain the separation to the LMSR. This has the effect of cycling the thrusters thru about 90 degrees of azimuth, a relatively tight range that makes them more responsive to any position error between the vessels. In the zero knots test, with the only 'load' coming from the position error the thrusters were repeatedly required to azimuth thru 180 degrees, which slowed their response, and increased the watch circle.

Figure 9: View forward during sea trial, vessels are in position for a crane transfer, and their relative watch circle is 1.5m

Figure 10: View aft during sea trial, vessels in position, aft fender touching, underway at 3.7 knots

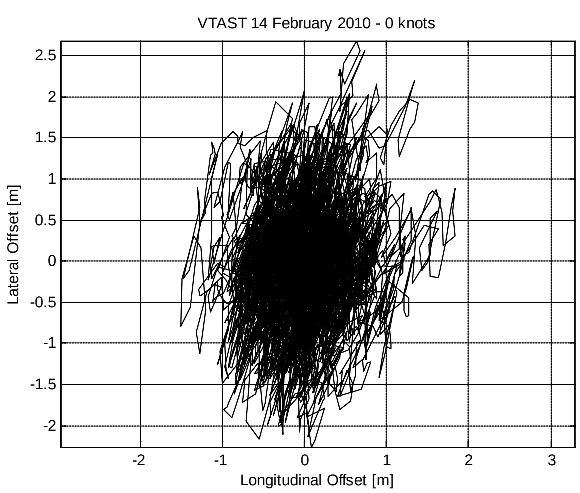

Figure 11: Relative Watch Circle between MS3 and LMSR, 0 Knots

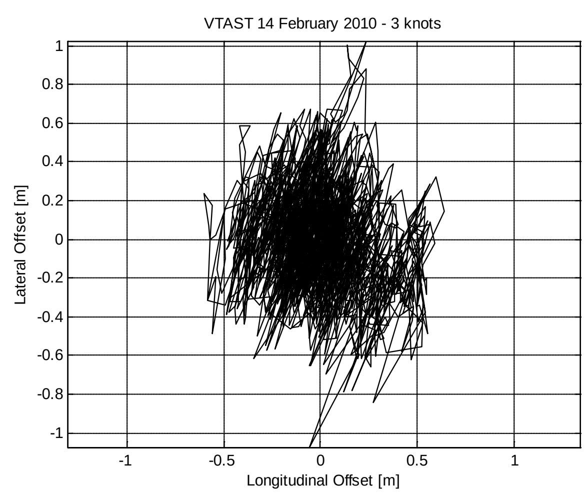

Figure 12: Relative Watch Circle between MS3 and LMSR, 3 knots

Phase 4 Heading Control

With the VTAST Sea Trial completed, and a baseline capability of a limited thrust MLP to interface with a heading controlled LMSR, STLVAST began to consider methods for the MLP to interface with a Container Ship that had no heading control, or low speed (and hence steerage control) capability. We had already begun experimentation and analysis of heading control technologies, and produced a Concept Summary Report (March 2010) that summarized our work and down selected to the two most promising Concepts:

- DP Pushing
- Stern Drogue

DP Pushing

The goal of DP Pushing is to avoid the use of mooring lines to keep the ships together. One ship can be considered DP Capable, while the other ship has no low speed propulsion or manner of keeping it's head to sea. Contact is possible between the ships using fenders. The idea is that the DP Pushing vessel controls the heading of the cargo vessel. It pushes the cargo vessel at a very low velocity into the waves. Both ships have zero to negligible forward speed.

Schematically, the DP pushing arrangement is given in Figure 13. The DP controller works in a relative mode alongside the container vessel. If DP pushing is enabled, a combination of an additional sway force and yaw moment is delivered to push the dead ship into the required heading.. The following motions are resulting in the following actions:

- When the dead ship moves forward with respect to DP pushing vessel, the DP pushing vessels moves with it. So the difference in surge motion is kept to a minimum.
- The relative lateral distance between the ships is kept at a value as constant as possible, the DP system attempts to keep the distance between the ships slightly less than the thickness of the fenders.
- When the bow of the dead ship moves to starboard, the DP pushing vessel performs a combine sway/yaw movement with the bow to portside. As such, the dead ship will experience a bow-to-starboard correction. Similar, when the stern of the dead ship moves to starboard, the DP pushing vessel pushes it's stern to starboard, and hence the stern of the Dead ship is pushed back to starboard.

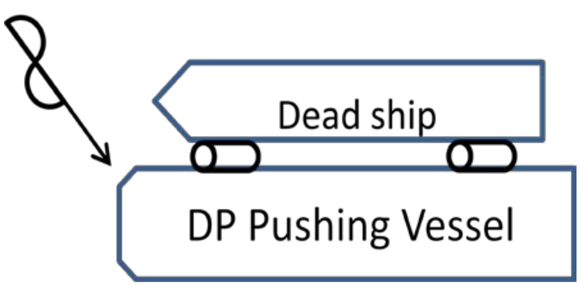

Figure 13: Schematic arrangement of MLP, container vessel and fenders

The required DP system is given in Figure 14.

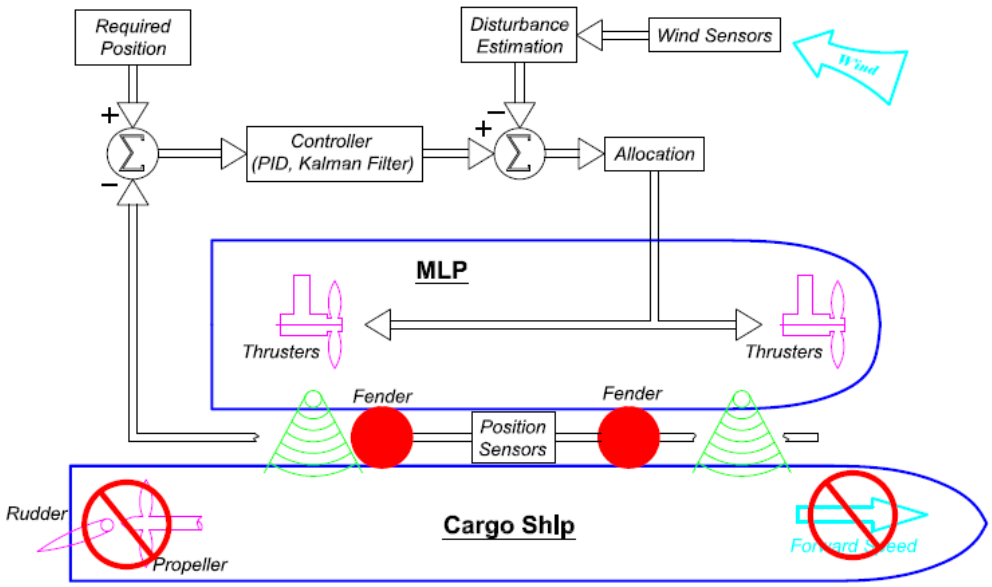

Figure 14: DP controller arrangement for DP Pushing

This system has been developed and tested in the model basin. Every aspect of the operation was tested and its performance demonstrated. A typical operation is given in Table 1.

Table 1: phases of DP pushing operation

Phase	Description
Approach of cargo ship	At dead slow, the cargo ship approaches
Engine shutdown of cargo ship	The cargo ship slows down to zero speed
Approach of MLP	MLP 'catches' the cargo ship, using joystick control
MLP alongside cargo ship	MLP comes alongside using relative DP (the follow target – option)
MLP enables DPpushing	MLP enables DPpushing and controls the heading of the cargo ship from this point.
MLP pushes cargo ship to desired heading	Using fenders only, the MLP pushes the Cargo ship to the desired heading (typically a bow quartering heading)
MLP stays in control using DP pushing	
Break away	DPpushing is disabled (heading of cargo ship in not controlled) and MLP breaks away (on relative DP) till it can switch to normal DP mode or normal control.
Cargo ship starts engine and takes off	

The DP Pushing concept was demonstrated in seastate 3 and in seastate 4. The MLP was able to control the heading of the cargo ship and stay alongside. The largest excursion in seastate 3 at the most favorable heading was 1.5 meter. It was found that the most favorable heading was between 30° and 45° off the bow, where the cargo ship was positioned at the weather side.

Stern Drogue

Stern drogues were considered for STLVAST as a way to slow down a commercial containership while still retaining heading control. The concept is to deploy the drogue while the propeller shaft is operating at minimum speed (idle) which is generally between 25% and 40% of rated shaft speed. By sizing the drogue properly the ship speed could be slowed from its idle speed (generally in the neighborhood of 5 to 8 knots) to approximately 3 knots. This reduction in speed makes STLVAST DP operations considerably easier. In addition, since the propeller would still be providing an accelerated flow over the rudder maneuvering control of the containership would be retained. It is important to note that drogues are essentially a technology for making a containership a more benign tracking target for an MLP. If adequate speed reduction and heading control are maintained the resulting MLP positioning performance is primarily influenced by the MLP DP system. Drogue design has focused on four key areas: drag coefficient, stability, structures, and deployment. Investigations on the last two issues, structures and deployment, are ongoing and will not be reviewed in the present article. Drag coefficient and stability have proven to be complex issues, with all model and field prototype drogues converging on a conventional hemispherical canopy with a center ventilation hole and guide surface. Full scale testing to date indicates stable operation with a drag coefficient of approximately 1.8. More information on drogue drag and stability can be found in Knacke [8], Cockrell [9], Hoerner [10], and Bradner and Harris [11].

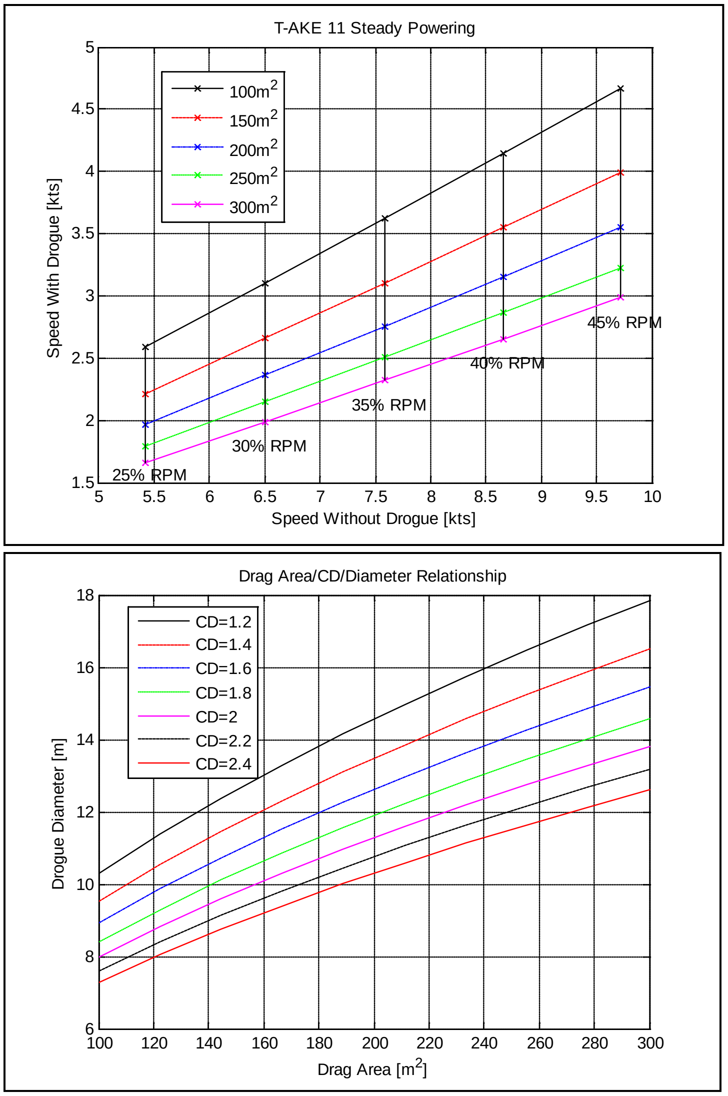

Figure 25 - Drogue Influence on T-AKE 11 Powering

A drogue must be sized correctly for it to be of benefit for seabase operations. The results of a sample sizing calculation for the T-AKE 11 is shown in Figure 15. The plot on the left shows how ship speed without a drogue (on the horizontal axis) and speed with a drogue (on the vertical axis) are related by drogues of varying drag area. Note that drag area is the product of drag coefficient and the projected area of a drogue, in this case the area of a disk with the nominal drogue diameter. Contours of constant shaft speed as a percentage of maximum are also shown. Thus, for example, at 35% shaft speed the T-AKE 11 would go 7.6 knots without a drogue, but would slow to a speed of about 3.1 knots with a drogue that has a drag area of 150 m^2. The plot on the right hand side shows the relationship between drag area and drogue diameter for a given drag coefficient (CD). For example, for 200 m^2 of drag area and a drag coefficient of 1.8, one would need a drogue of 10.3 m diameter. This exercise has been repeated for various ships of relevance to seabasing operations but will not be presented.

Single ship, calm water maneuvering tests with a notional containership at MARIN in April/May 2010 have shown that maneuvering characteristics are generally improved with a drogue. This is believed to be partially due to the increase in water flow velocity over the rudder. Tactical diameters are decreased but the advance is increased, likely due to the stabilizing effect of the drogue. One unusual result is that the drogue usually sets up slightly to one side or the other of the ship resulting in asymmetric maneuvering performance.

Drogue tests in a seaway at MARIN indicated very high transient tow cable loads which were decreased substantially by introducing springs and hanging weights. Corresponding full scale experiments currently in process are indicating transient loads which are substantially lower. It is believed that additional elasticity in the canopy, shroud lines, and tow cable at full scale which were not modeled accurately in the tank contribute to this discrepancy.

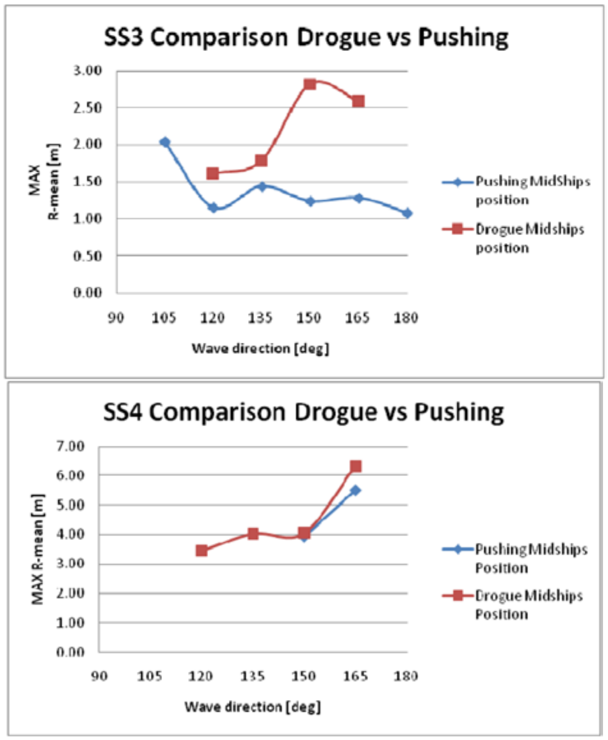

Figure 16 - Comparison of Drogue and DP Pushing

The DP positioning performance with a drogue at 3 knots and using DP pushing for seastates 3 and 4 is shown in Figure 16. In sea state 3 DP pushing appears to be better than drogue operation. In sea state 4 however the two methods yield similar results.

Concluding Remarks

Three years ago ONR awarded Oceaneering's Team the contract for STLVAST. We have experimented with cycloidal propellers, wave feed forward, DP pushing and stern drogues, and demonstrated Close In Precision DP at a full scale sea trial. Working with some of the world's best marine engineering companies we have innovated and produced, we hope, some interesting insights and useful advances in the science of Dynamic Positioning.

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