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DYNAMIC POSITIONING CONFERENCE
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New Applications

A Tighter Watch Circle at Higher Speeds

Dr. Gregory Hughes
Oceaneering International

Dr. Rick Harris
Maritime Applied Physics Corporation (MAPC)

Frans Quadvlieg,
MARIN

Abstract

Introduction

In the Summer of 2007 the Office of Naval Research (ONR) initiated a technology development program called STLVAST (Small to Large Vessel At-Sea Transfer). The goal of this program is to develop “enabling capabilities” in the realm of logistic transfer (i.e. stores, equipment, vehicles) between a large LMSR vessel (270m, 62,000t) and a smaller ship (168m, 75,000t). Beginning as one thread amongst several complimentary capabilities, dynamic positioning has developed as a core capability with potential application to future seabasing operations. However the seabasing operational environment can be extreme, and requires safe position keeping when the vessels are in close proximity, at ahead speeds, and in high sea states. This paper discusses the initial development and successful testing of an innovative approach using cycloidal propellers to achieve the objectives of what we call Close-In Precision (CIP) DP, as well as the current development of a wave feed forward (WFF) technology that has broader application in any existing DP architecture.

Why Do We Need to Safely Drive Two Ships at 8 Knots, 25 Feet Apart?

The quick answer to this is because the US Navy (USN) has a vision to supply humanitarian aid or project military power, without the use of any traditional port or shore based facilities. However troops, equipment and supplies must still be delivered ashore, and so a “port at sea”, the sea base, is required. In turn the sea base therefore requires this logistic transfer to occur between large vessels, at sea, underway and in higher sea states, and from these operational needs flows the requirement for CIP DP.

The goal of the Office of Naval Research (ONR) is to “foster, plan, facilitate and transition scientific research in recognition of its paramount importance to enable future naval power and the preservation of national security.” To this end, ONR invests in several areas of Science and Technology, including Discovery and Invention (D&I), Future Naval Capabilities (FNC) and Innovative Naval Prototypes (INP). As seen in the following figure, STLVAST (Small to Large Vessel At-Sea Transfer) is an FNC. FNCs generally start with a Technology Readiness Level (TRL) of 3 or 4 (proof of concept to component validation in a laboratory environment) and are transitioned to an acquisition program office at a TRL of 6 (demonstration in a relevant environment).

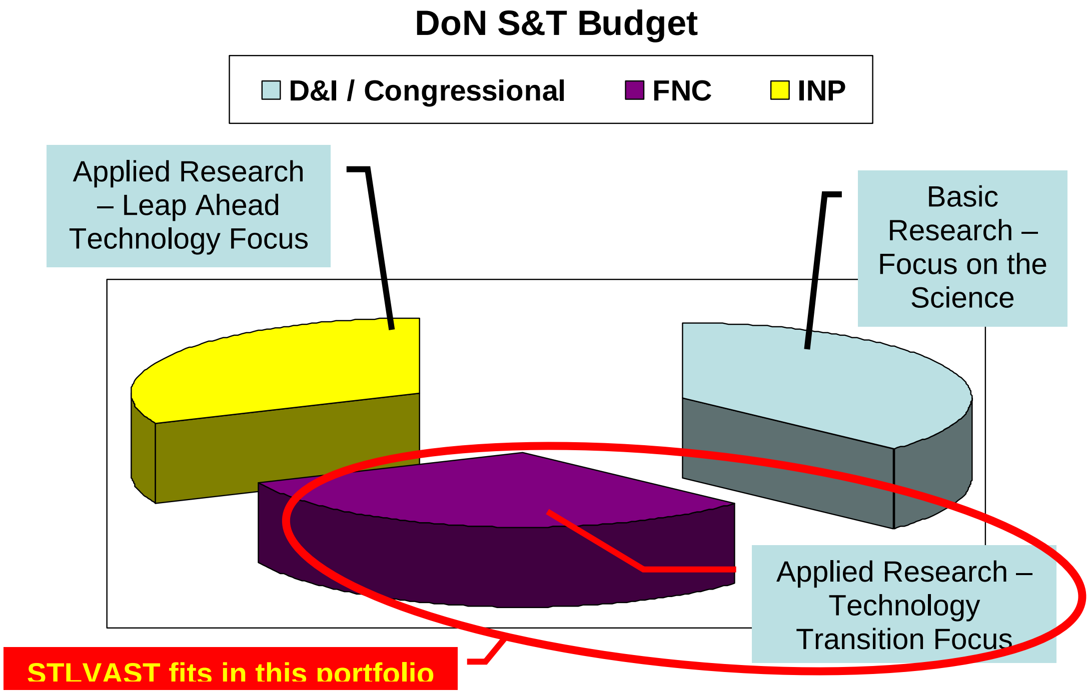

Figure 1. STLVAST in the context of ONR investments

FNCs are aligned with the four pillars identified in Seapower 21, the Navy’s top level vision document and a couple cross-cutting focus areas. The pillars are Sea Shield, Sea Strike, Sea Base, and FORCEnet,. The STLVAST program supports the Navy’s Sea Base pillar. The Seabasing Concept addresses the following tasks, typically referred to as CAESaR:

- Close a Marine Expeditionary Brigade-sized force within 10-14 days
- Assemble a Marine Expeditionary Brigade-sized force within 24-72 Hours
- Employ one battalion vertically and one battalion via surface within 8-10 hours
- Sustain selected joint forces and up to two brigades operating up to 150 nm inland with minimal logistics footprint ashore
- Reconstitute forces for future operations within 30 days

Three of the above tasks (assembling, sustaining, and reconstituting) require the at-sea transfer of personnel, vehicles, and break bulk / containerized cargo to enable transfer to / from surface connectors. This at-sea transfer will bring ships much closer than previously required (due to reach limits of the transfer crane), and Close-In Precision Dynamic Positioning (CIP DP) is a key technology needed to successfully position two ships as close as 25 to 15 feet for transfer operations while moving forward in the seaway.

Therefore an increase in dynamic positioning capability is required by STLVAST, so new technologies and innovation are required to improve the position keeping accuracy of dynamic positioning systems. There are two fundamental aspects to the challenge of keeping two large vessels safely alongside each other, without resorting to fenders and mooring lines, they are:

- Sensing of the relative position and orientation (of most interest are the surge, sway and yaw DOF) of each vessel to the other, at an update rate fast enough to support thruster reaction
- A thruster architecture or technology capable of responding quickly enough to provide the required correcting dynamic force

Several mature sensing technologies, capable of providing the relative position of the two vessels, are available based on either radar or laser techniques. Although the update rate of these devices (typically 1 Hz) is currently too slow for the STLVAST requirement, there doesn't appear to be any reason that the device update rate could not be improved with some investment. The other technical challenge therefore is the development of a "higher bandwidth" thruster capability. In this respect higher bandwidth means, an ability to provide the required thrust force, in the required direction, faster than typical COTS thruster systems.

STLVAST Requirements and Why we Need to Improve Thruster Performance

From the higher level seabasing operational requirements flow STLVAST system requirements, from which flow the CIP DP technical requirements that are presented in Table 1. Two vessels have been defined to allow the development and testing of technology. These vessels are the Dockwise Mighty Servant 3 (MS3) and a Large Medium Speed Roll-On/Roll-Off (LMSR) ship.

Parameter	Metric	STLVAST Threshold	STLVAST Objective
Vessel Speed	Forward speed of MS3 alongside an LMSR while safely transferring equipment, under Dynamic Positioning (DP)	0-8 knots	
Safe Separation Distance between MS3 and LMSR	Distance maintained in high Sea State 4 without ship-to-ship impact using DP	15 feet	25 feet
Sea State, as Defined by NATO STANAG 4194	Ambient sea conditions under which MS3 operations can be performed safely	Low Sea State 4	High Sea State 4
Time to Maneuver Alongside	Time from MS3 being in the vicinity of the LMSR until first transfer can begin	2 hours	20 minutes

Table 1: STLVAST Requirements

These requirements are the constraints within which our CIP DP solution must be developed, and from which the performance parameters of the dynamic positioning system, such as watch circle radius, are derived. Of interest is the context for the three dominant requirements:

- Vessel Speed 0-8 Knots: This ahead speed range was chosen because in the future the seabase may interface with commercial container vessels. Many of these vessels have no DP capability, main propulsion gearboxes, or controllable pitch propellers and hence cannot maintain steady headway at low speeds (< 4 knots), hence the need to maintain position with a vessel underway at up to 8 knots
- Safe Separation 15-25 Feet: A potential future need is to support the movement of containers by crane between the vessels. This scenario could mean a separation of between 15’ to 25’, to support the limited reach of a marine crane. At these closest approaches fenders may be deployed for protection, but mooring lines cannot be used because of the risk to deck crew and equipment.
- Sea State 4: As the seabase operates over the horizon from the shore, in the “blue” ocean, ability to operate in a high sea state 4 increases the operational window.

Therefore the STLVAST CIP-DP operating scenario differs from typical DP applications in several important respects. The first difference concerns the relevant environmental disturbances. The addition of a second ship creates wave diffraction and “bank effect” hydrodynamic loads and in addition ahead speed increases sway/yaw coupling of the maneuvering ship. The presence of a second ship also modifies the wind flow and corresponding loads, although these effects were not considered in the present study. Ship positioning requirements are tighter and more critical due to the close separations. Furthermore, ahead ship speeds can dramatically reduce the effectiveness of typical DP thrusters. Each of these issues needed to be investigated to develop a system capable of providing the desired performance.

Hydrodynamic Disturbances

Standard analysis of free floating dynamic positioning systems consider the environmental disturbances to be essentially a superposition of wave and wind loads. Low frequency second order and mean drift wave disturbances are the main focus of analysis. These can result in large amplitude position oscillations and persistent transport of the vessel away from its intended position. Zero mean first order wave disturbances which occur at wave encounter frequency and are proportional to wave amplitude are normally ignored since their resultant effect on ship motions cannot be controlled by reasonably sized actuators. The physical origin and practical procedures for calculating these loads are described in Faltinsen [REF-1]. Wind loads are a result of the aerodynamic drag and lift generated by the ship structure above the waterline and are calculated from wind tunnel experiments or empirical methods, Fossen [REF-2].

The CIP-DP scenario introduces two new hydrodynamic disturbance mechanisms, both due to the presence of the LMSR. The first is the distortion to the incident wave field and the second is the introduction of “bank effect” disturbances to the flow about the MS3. The “bank effect” loads are called such because they are similar to the disturbances experienced by ships operating near a canal banks or passing other ships.

The incident wave field distortions were investigated by comparing MS3 mean wave drift loads calculated by SAIC’s LAMP [REF-3] nonlinear time domain seakeeping code with and without the LMSR present at various wave directions and ship separations, all at zero speed and sea state 4. The analysis showed that the second ship generally reduces sway drift loads, especially in beam seas, and that yaw moments are somewhat similar in amplitude and dependence on incident wave direction for both the single and two ship scenario. Both sway and yaw disturbances were modest functions of ship separation.

The overall conclusion was that the second ship did not severely alter the magnitude of the wave hydrodynamic disturbances.

The bank effect loads were investigated by comparing estimates of MS3/LMSR interactions based on empirical methods (Lewis [REF-4]) with results from a Kongsberg capability analysis (StatCap) for a notional concept MS3 with cycloidal thrusters, developed by Oceaneering for the purpose of the STLVAST program, in an attempt to gauge the magnitude of the bank effect loads relative to wave and wind loading for single ship positioning scenario. Figure 2 shows the results of this comparison. These plots show the resulting predictions for sway force and yaw moment at 8 knots speed for the MS3 and LMSR as a function of lateral and longitudinal separation. Three other lines are also plotted on these figures. Two are the minimum and maximum values of the combined wind and wave sway force or yaw moment (including dynamic allowance) from the Kongsberg study. The third lines are vertical and show the longitudinal spacing for the base arrangement for cargo transfer operations.

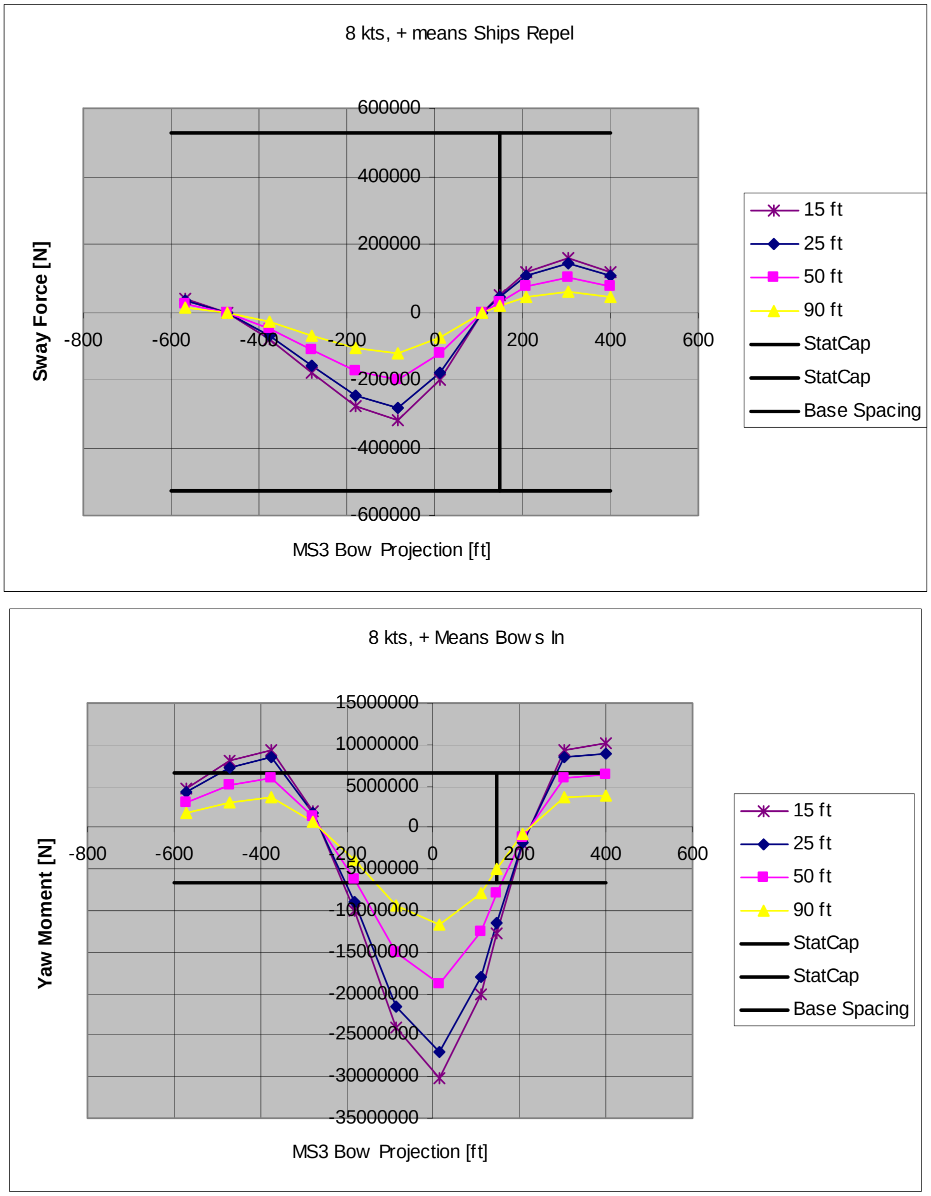

Figure 2: Comparison of Typical DP and Bank Effect Loads.

The main conclusion from these figures is that bank effect sway forces are fairly small in the context of ordinary DP disturbances, but the yaw moments are quite large and a strong function of relative position. At the base longitudinal position of the MS3 and LMSR the yaw moment is not too great, but it can increase dramatically with small changes in position. This effect would thus be of great significance if the MS3 was overtaking the LMSR from astern at small ship separations and high ahead speeds. It also might prompt MS3 operators to, as an alternative, approach a moving LMSR by first establishing longitudinal position and synchronizing speeds from a large lateral separation and then gradually reducing the distance between the ships.

In addition to these effects, ahead ship speed increases the hydrodynamic coupling between yaw disturbances and sway disturbances. The dominant physical mechanism is the side force and yaw moment caused by hull sideslip. This coupling can be accounted for in the controller structure and is described below.

Positioning Performance

As stated above, the STLVAST CIP-DP system was intended to ultimately allow ship separations of 16 to 25 feet at ahead speeds of 8 knots in sea state 4. To prevent collisions and allow for zero mean first order wave frequency motions of both the MS3 and LMSR (which effectively reduce the separation “margin”) this corresponds to a 2 meter relative watch circle and 1 degree relative heading performance requirement.

These strict positioning requirements meant that the open loop crossover frequency of the control system needed to increase above that which is found on typical DP systems. This increase in bandwidth could be accomplished by two modifications to the control system. The first modification was trivial and simply involved increasing the controller gains in the outer loop PID control network to provide the desired disturbance rejection. The other modifications involved increasing the bandwidth of both the ship position filtering and actuator (thruster) systems to correspond to the demands of the new outer loop control.

For the testing, the control loop tuning was performed with computer simulations of the MS3 and by in situ tuning of the model control system on the tank carriage. The ship position filtering was initially modified by tuning Kalman filter gains on the tank carriage and, ultimately, by bypassing the Kalman filter and using measured position directly. The actuator bandwidth issue was approached by seeking ways to improve the performance of, or replace standard DP thruster arrangements.

Actuator Bandwidth and Effectiveness

Typical DP systems use azimuthing thrusters to control the vessel position. Units appropriate for ships the size of the MS3 can typically take as much as 60 seconds to completely perform one complete thrust reversal cycle. Simulation analysis of the MS3 with the MARIN code DPSIM showed that this response was too slow for the loop bandwidth required to meet the STLVAST positioning objectives. Thus, a set of actuators with faster response time was needed. In addition to the bandwidth, there was an additional difficulty with using conventional azimuthing or tunnel thrusters for this application. The CIP-DP system needs to work at ahead speeds of up to 8 knots. But the ability of conventional thrusters to generate lateral force decreases dramatically with forward speed, losing as much as 75% of their effectiveness at 8 knots [REF-5].

The bandwidth and effectiveness problems were both addressed by choosing Voith-Schneider cycloidal propellers (VCP) for the CIP-DP application. Cycloidal propellers consist of vertical rectangular blades that can be controlled to pivot individually about a spanwise axis and are arranged around the perimeter of a disk mounted flush to the hull surface and is able to rotate about a vertical axis. Their operation is controlled by the orbital velocity of the blades and two independent degrees of freedom in the linkage which controls the blade position throughout the orbit. This arrangement allows independent selection of longitudinal and lateral force developed by the unit. Since the linkage has relatively low inertia, the complete thrust reversal cycle for units appropriate for the MS3 can be accomplished in less than 10 seconds. Voith also manufactures a variant of the VCP, the Voith Cycloidal Rudder (VCR). VCRs are dual mode VCPs which are intended for use directly behind a conventional propeller. At transit speeds the ship is propelled by the propellers, the orbit velocity of the VCRs are set to zero and the blades are manipulated like conventional rudders. At lower speeds the VCRs begin to spin and are actuated like VCPs.

The thrust and torque characteristics of a cycloidal propeller can be summarized on a polar diagram such as those found in Ficken and Dickerson [REF-6]. These were used to size units for the MS3 model tests, four 3.8MW units were selected, two forward, and two aft. Cycloidal propellers are typically used to provide forward and reverse propulsion, in addition to their maneuvering capability, in commercial applications. For our first test of CIP DP we decided to dedicate the VCPs to providing DP thrust and steerage on the MS3 model, and use the MS3's conventional propellers to provide forward propulsion. An additional simplification was to use four VCPs rather than two VCP's forward and two VCRs aft.

<u>Will it Work in the Test Basin?</u>

A series of model tests were conducted to investigate the effectiveness of cycloidal propellers in the STLVAST application. To perform these test series, Mighty Servant 3 was equipped with 4 Voith Schneider Cycloidal Propellers as shown in Figure 3. Two VCPs were mounted in line in the foreship and two VCPs were mounted aft in place of rudders.

Figure 3: Photographs with fore and aft ship of Mighty Servant equipped with Voith Schneider propellers

The forward VCPs and aft VCPs were each steered as separate groups to give longitudinal force, transverse force and moments as commanded by the DP controller. The main propellers were used to provide a constant forward thrust.

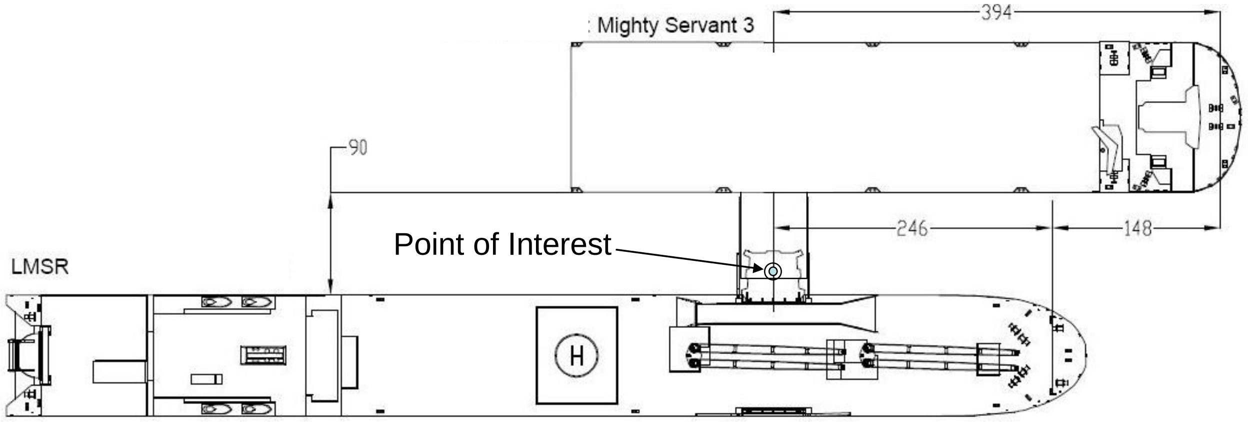

Figure 4: Location of Mighty Servant 3 (top) and LMSR (bottom) with respect to each other

Incident wave directions tested were bow, bow quartering, beam waves and stern quartering (all waves coming from LMSR direction, with MS3 in the lee of the LMSR). Both ships were free swimming (not attached to the basin carriage in any way), were autonomously self-steered, and both used a DP controller, although the LMSR only had conventional shaft-driven twin propellers each with a rudder and two bow thrusters. The LMSR was commanded to drive ahead (at zero knots to maintain station), at the required speed, and maintain a fixed heading. The MS3 was commanded to "slave" to the LMSR "master" and maintain an athwartships separation and match the heading and speed of the LMSR. The MS3 was therefore controlled such that the Point of Interest (POI) of the MS3 stayed on top of the POI of the LMSR. This is illustrated in Figure 4, the POI's of each vessel representing the nominal position of a ramp between the ships. In this first testing no physical ramp was used between the models.

Control System Structure

A feedback system was designed to control the sway/yaw dynamics of the MS3 and allow it to maintain station alongside another ship. The system used in the tank experiments was developed by MARIN and was approached by first separating the lateral sway/yaw dynamics from the surge dynamics. The surge control consisted of a constant speed screw propeller which provided most of the required thrust and then using longitudinal position error through a PD feedback loop to control ordered VCP thrust.

The lateral control system consisted of uncoupled PD feedback loops for both the relative lateral separation error and the relative heading error. Thruster allocation algorithms converted ordered force/moment commands into rate and pitch commands for the VCP/VCR units. Additional coupling for the lateral control system intended to compensate for the hydrodynamic sway/yaw coupling were considered but were not demonstrated in the tank experiments.

The test matrix consisted of the following tests

- Single ship tests on Mighty Servant 3 to judge and optimize the DP controller. Carried out in calm water and in seastate 3 and 4.
- Side by side tests in
  - Speeds of 0, 4, 6, 8 knots,
  - Mutual distances of 30m, 7.5m and 5m;
  - Seastate 3 and seastate 4
  - Wave directions 180°, 150°, 120°, 90° and 60°
  - Some alternative steering settings of the VSP and experimentation with the Kalman filter.

- Each test simulated a minimum of 70 minutes of full scale operation.

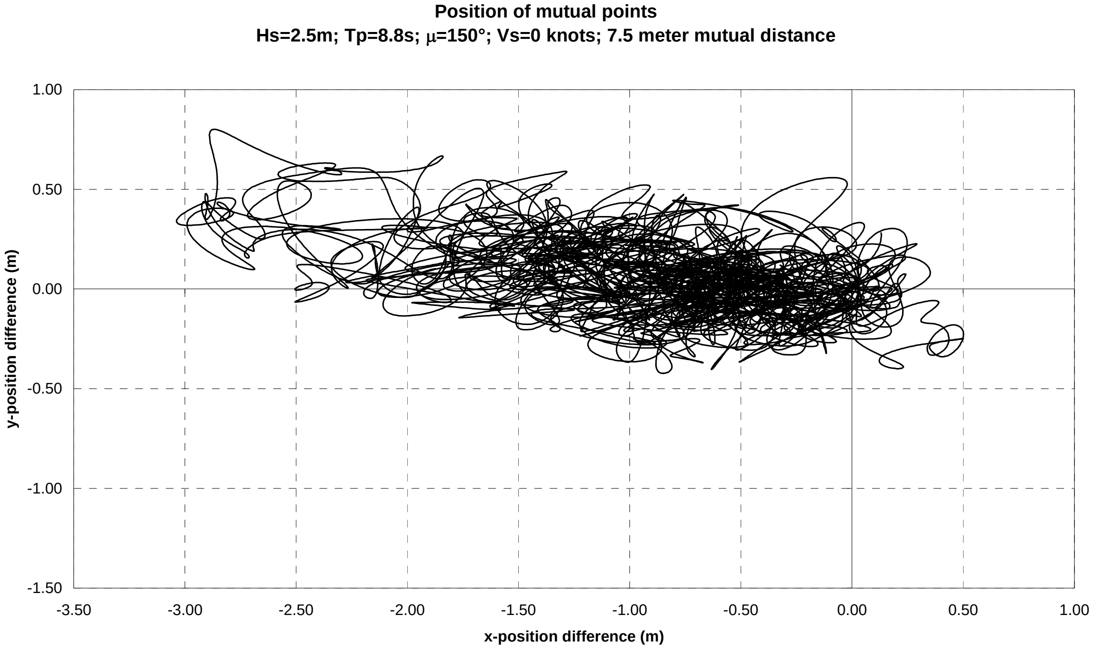

Figure 5: X-Y-plot of MS3 / LMSR Separation

The test results are presented as the maximum value of R_{centre} observed during a particular test. R_{centre} is defined as the radius of the watch circle between the ordered and average position of the MS3 relative to the LMSR. The value of R_{centre} was calculated from time series data of the MS3 position with respect to the LMSR, an example of which is shown in Figure 5. The maximum values of R_{centre} were used instead of, for example the rms values, because for these experiments the maximum was felt to be the best, most physical metric for performance. The average position was used as a reference because the feedback loops did not have integrators to reduce the 'steady' offset. Integrators were not used in the model experiments because in the forward speed cases the model basin was too short to permit runs long enough to allow the integrators to reach equilibrium values. Further details on all these points can be found in REF-8.

High Speeds, High Seas and Close and Nothing Sank!

The STLVAST CIP-DP program looked at improving existing DP system capabilities in an incremental fashion by first examining relatively high ahead ship speeds and large ship separations (fast and far) followed by low ship speeds and close separations (slow and close). The final objective of high ahead speeds and close separations was left to last.

Fast & Far

This scenario investigated large ship separations and ship speeds up to 8 knots. The relationship between positioning error and wave direction for the 'fast and far' regime is shown in Figure 6. This figure includes ship speeds of 4 and 8 knots and ship separation of 30 meters. All runs are at the top of sea state 4. It indicates that the positioning errors are minimal in head seas (180 deg) and increase progressively as the relative angle decreases. For bow and bow quartering seas the maximum deviation remains within a range of 3 meters.

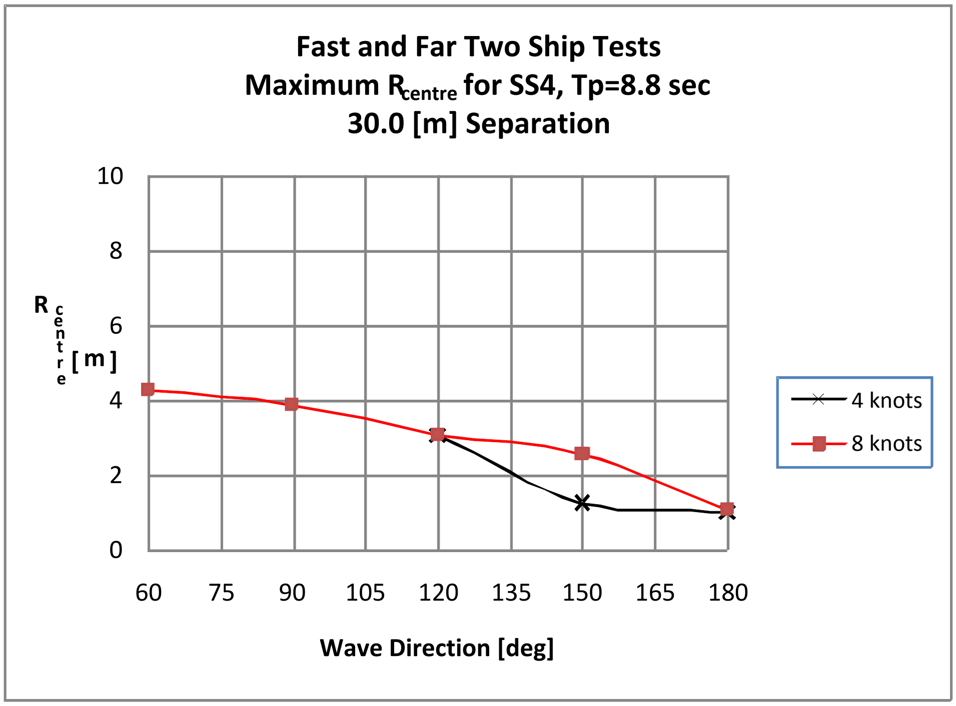

Figure 6: R_{centre} as function of wave direction for 30m Separation

As the figure shows, DP performance was excellent, for all headings tested, and all speeds. Tests run sea state 3 showed an even tighter watch circle, which for bow quartering seas was less than 1m.

Close & Slow

This scenario, ‘close & slow’, would typically be encountered when performing cargo transfer with cranes. In this scenario, the ships needed to be very close together. The relationship between positioning error and wave direction for speeds of 0 and 4 knots is shown for a ship separation of 7.5 meters in Figure 7. This plot shows that the dependence of maximum R_{centre} on wave direction is not monotonic as in Figure 6. It is worth noting that the rms value of R_{centre} displays the same trend.

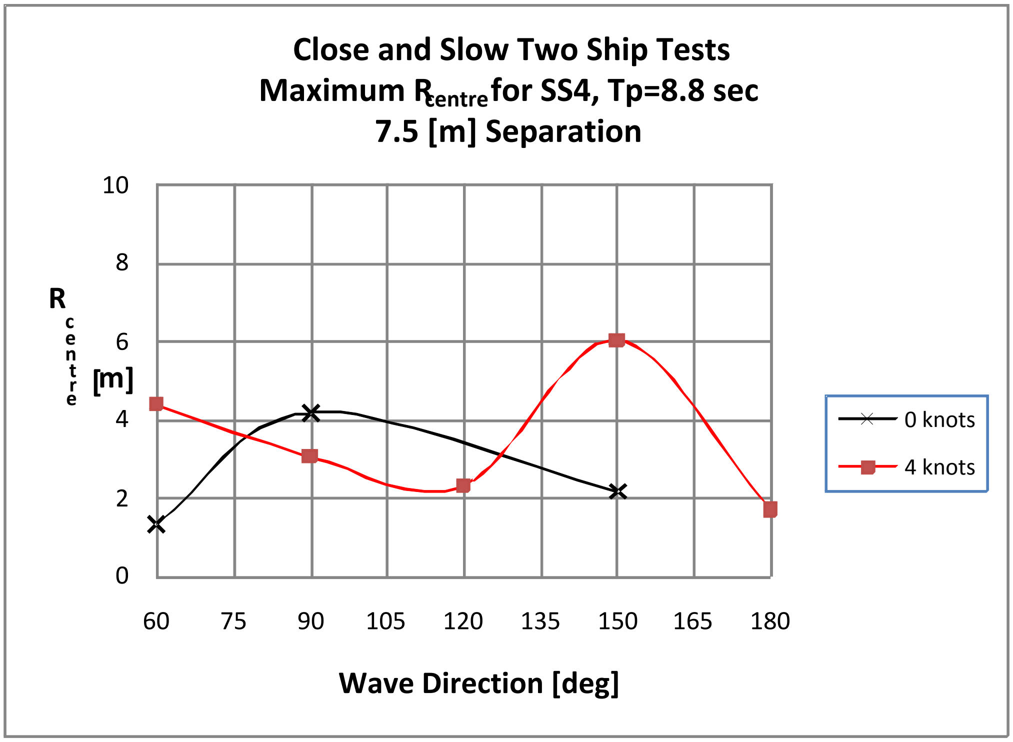

Figure 7: R_{centre} as function of wave direction for 7.5m Separation

It is not clear why the dependence on wave heading is less orderly at the closer ship separation of 7.5 meters. In particular, the large deviation (6 m) shown in bow quartering (150 deg) waves is quite different from that experienced at 30 m separation (1.3 m) and as well as the deviations at other wave headings at 7.5 meter separation. One thought based on observation of the tests is that the decreased spacing increases the magnitude of the diffracted and reflected waves between the two hulls. When the waves are approaching the two ships with the MS3 to leeward with its bow extended, the waves seem to 'pile up', scatter, and interact with the Kelvin wake system in ways which are qualitatively different from the interactions noted at other wave directions. This effect seemed to be particularly pronounced in the long crested waves used in the tank.

The MS3 remained stable with the VSPs, and did not contact the LMSR in any of the 7.5m runs. The confused, and apparently amplified seas between the hulls did break over the rear deck of the MS3, but the CIP DP system always brought the MS3 back into safe alignment with the LMSR.

Fast & Close

For the final test of the series we decided to allow the VCPs to draw as much power as they required to maintain station in the most severe environmental-operational condition (7.5m separation, 8 knots and high SS4). Whereas an earlier attempt using the 3.8MW setting on the model VCPs had indicated an instability, the "8MW" VCPs performed superbly, driving the MS3 safely up the tank alongside the LMSR, with an R_{centre} of less than 3m!

Dependence on Ship Speed and Separation

The preceding data can be used to prepare cross plots of R_{centre} maximum as a function of ship speed and separation. These plots are shown in Figures 8 and 9. It should be noted that these plots also include an additional data point of 7.5m separation and 8 knots ship speed (our ultimate Fast & Close test) and are all for bow quartering seas.

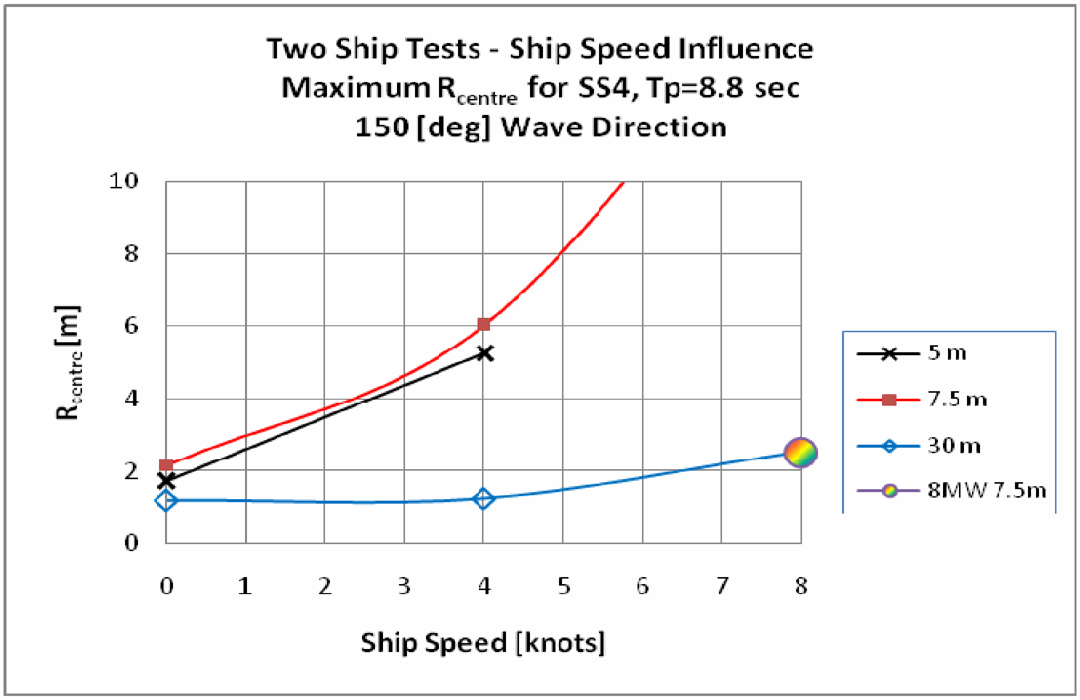

Figure 8: R_{centre} as function of Ship Speed

Figure 8 clearly shows that tracking error increases with ship speed, although more severely at closer separations than when the ships are further apart. The increased error is considered to be a result of the diffraction and scattering effects and bank effect hydrodynamic disturbances. By increasing the available power to the VCPs we were able to achieve excellent position keeping performance, at 8 knots, and at 7.5m separation. This data point is shown in Figure 8 as a larger circle. Figure 9 shows the same data plotted as a function of separation distance. The plots for 0 and 4 knots suggest that there is a maxima in the positioning error somewhere between 5 and 30 meter ship separation in this particular seaway.

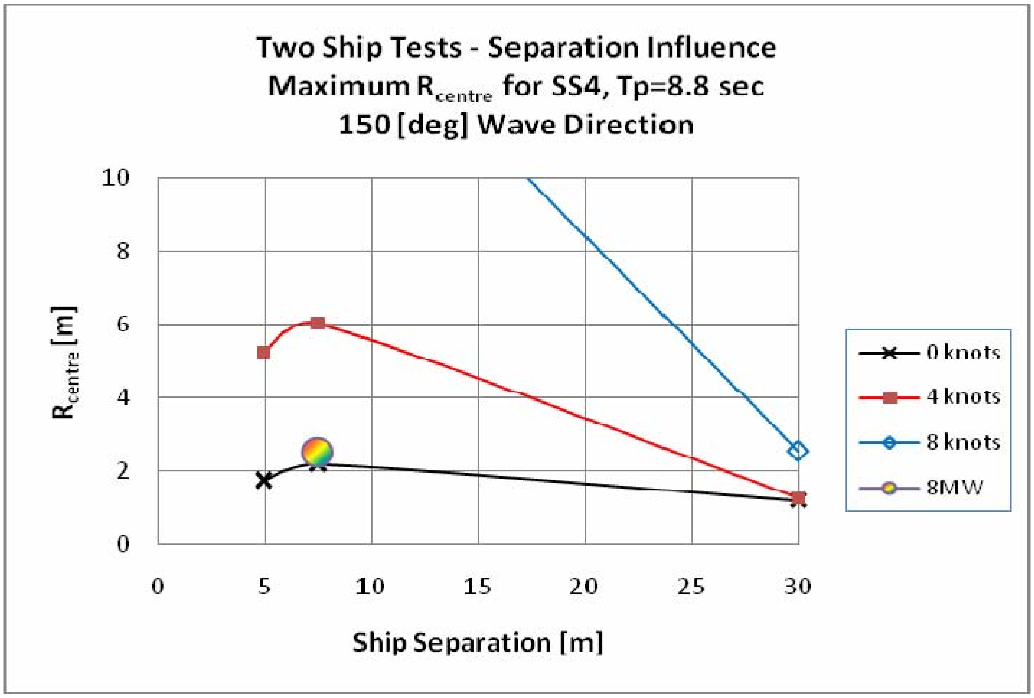

Figure 9: R_{centre} as function of Ship Separation

What Next?

These test results indicate that using a higher bandwidth thruster, capable of producing control thrust effectively at higher forward speeds, appears to be effective in meeting the position keeping capability of large vessels in the range of STLVAST speeds and sea conditions. As noted below, a comparison of similar capabilities with other thruster architectures is underway and neither the relative performance merits or the ship integration benefits / challenges were addressed under the limited effort being reported in this paper. The use of VSPs in ships of this size is not widespread, so it is clear that there are some downsides to the use of VSPs for general seagoing commercial ships. However, this initial set of tests indicate that VSPs could provide a niche capability and should be considered in the design trade space for ships with highly precise relative positioning requirements at ahead speed.

Since the STLVAST program may need to be adapted to existing ship propulsion / thruster architectures to support the Seabasing concept, the focus of the STLVAST program has shifted away from VSPs which are a mature technology to developing technology solutions that are applicable to a wide range of thruster architectures. The primary focus of STLVAST going forward is the application of Wave Feed Forward (WFF) control system.

WFF Technology

Ship dynamic positioning systems have long used both feedback and feed forward approaches to environmental disturbance rejection. The advantage of feedback control is that it does not require accurate foreknowledge of the disturbances to the system, but the disadvantage is that the error between the desired and actual state of the system must accumulate for the control system to take action. Feed-forward is fundamentally different in that it directly responds to a disturbance without measured error of the desired state. The advantage is that it can counter the influence of a disturbance to the system directly and does not require errors to accumulate. The disadvantage is that it requires an accurate estimation of the disturbance in order to use the actuators properly.

Since both feedback and feed-forward control have complementary strengths and weaknesses, combining them can be a powerful technique. The feed-forward elements address disturbances that can be measured or estimated well and feedback handles the rest, including positioning errors resulting from inaccuracies in the feed-forward control. This combined feedback / feed-forward approach is used with all modern dynamic positioning systems. However, the state of the art presently only includes feed-forward of wind disturbances. In the next round of work the STLVAST CIP-DP program will attempt to add wave disturbance feed-forward control for CIP-DP.

Wave feed-forward (WFF) for dynamic positioning systems have been under consideration for at least a generation by researchers in the Netherlands associated with the Technical University of Delft, and/or MARIN. This research has focused on the fundamental physics of wave disturbances and the practical implementation of control systems based on the resulting insight. Much practical work in the analysis of these second order effects has been accomplished by Pinkster and colleagues using a systematic analysis of the unsteady potential flow about a structure floating in waves. This work is based on an orderly Taylor series expansion of the potential function and resulting ship motions, thus terms of second order can be clearly and consistently identified. The main result is that most of the second order wave loads can be identified by persistent measurement of the relative wave height at various stations around the ship.

The STLVAST CIP-DP next efforts will attempt to develop this approach by investigating this and related methods of predicting the second order wave disturbances to a floating vessel, at ahead speeds, and in the presence of a second alongside vessel. The related methods are expected to include (1) measurement of the relative waterline around the ship as mentioned, (2) sensing of the hydrodynamic pressure on the ship hull and (3) a method based on precise measurement of ship accelerations. Ultimately accurate prediction of second order wave disturbances will be used to improve dynamic positioning using feed forward, and other related algorithms.

Conclusion

The results of the first phase of the STLVAST CIP DP development and testing indicate that cycloidal propellers offer potential to meet the performance specified in the STLVAST CIP DP metrics, and it seems likely that they can provide this new capability in addition to their more traditional propulsive and roll mitigation functions. Current efforts are focusing on assessing the effectiveness of using wave feed-forward techniques to improve dynamic positioning. If the testing is successful the US Navy is considering developing this WFF CIP DP capability from its current theoretical state to a mature large-scale demonstration system.

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