NUMERICAL PREDICTION OF Z-DRIVE ROLL REDUCTION CAPABILITY

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SUMMARY

This paper presents results of numerical predictions of the ability of a Z-drive propulsion system to affect roll stabilization of a vessel moving at steady speed in regular seas. The potential flow based, time domain, seakeeping and maneuvering code MOTSIM was used to evaluate the effectiveness of a twin Z-drive propulsion system on a vessel to control roll motions in regular seas. Results for several headings and wave characteristics were generated and compared with the roll reduction capabilities of a conventional rudder/propeller system on the same vessel.

1. INTRODUCTION

Recently, a set of physical model tests was performed at the National Research Council's Institute for Marine Dynamics. This seakeeping study focused on the response of a vessel in regular waves using a self-propelled model (twin Z-drives acting in tandem) equipped with an autopilot. It was observed during the tests that in bow quartering and stern quartering seas, that roll amplitudes were significantly higher than expected. It was proposed that the Z-drives, controlled by the autopilot to retain a giving heading angle, were accentuating the roll under these conditions. This observation that Z-drives can have a substantial impact on roll response led to the current study in which the Z-drives are used to reduce roll action in waves through implementation of an appropriately tuned control system.

Predictions of the effectiveness of Z-drive roll stabilization were performed using the code MOTSIM. These predictions are compared with MOTSIM predictions of roll responses of an unstabilized vessel and a vessel with a conventional propeller/rudder propulsion system.

2. BACKGROUND

Discussions of rudder roll stabilization (RRS) have been around since the early 1970's, with actual implementations on naval vessels during the 1980's (Fossen, 1994). Other types of roll stabilizing systems include:

- Fixed fins
- Retractable fins
- Anti-roll Tanks
- Bilge Keels

The RRS and fin systems are active (require a closed-loop control system) while the tank and bilge keels are passive. These systems have various advantages and disadvantages in terms of cost and effectiveness. RRS systems have the benefit of being relatively cheap to implement, since they do not require a special actuator (the ship is already equipped with a rudder), and are reasonably effective (as good as an anti-roll tank) in reducing roll. Z-drive roll stabilization (ZRS) would also be cheap to implement and could potentially be as effective as RRS, as they share same principles of operation.

3. RRS CONTROL SYSTEMS

From a control systems standpoint, ZRS is very similar to RRS, and both are a challenging problem for a number of reasons:

- Limited control authority: The rudder is an imperfect actuator because of its limited rate of turn (slew-rate) and the loss of lift at steep incidence angles (saturation) and/or at low speeds.
- Single-input/double-output (SIDO) system: Rudder angle affects both the yaw and roll of the vessel. The simplest control systems are single-input/single-output (SISO) systems.
- Non-Minimum Phase (NMP) System: A control systems engineering term that comes from examining the phase response of a system. The phase transfer function of rudder angle to roll angle for all vessels is dominated by this NMP behaviour and can make roll difficult to control using the rudder.

A closed-loop system relies on the fact that an actuator produces a predictable direction of response in a system. For example, if a heater is turned on in a room, the temperature goes up; i.e. positive heat generates positive temperature change, and reduced heat likewise reduces the temperature. For a marine vessel, the NMP behaviour results from the fact that the vessel's roll response goes through a 180-degree phase shift over the range of frequencies of interest; i.e. positive rudder action can produce both positive *and* negative roll responses. This behaviour is shown in the frequency domain plot of the rudder/roll phase transfer function in Figure 1 below. The phase transfer function shows that the response of the vessel in roll is 180 degrees out of phase of the rudder, whereas at lower frequencies, we have a more in phase relationship.

The illustration in Figure 2 demonstrates this behaviour. Initially, when the rudder is moved to port, the vessel rolls to port due to the roll moment induced by the rudder force. However, moving the rudder to port also causes the vessel to turn to port in yaw. Once this turn has settled in, the vessel then rolls to starboard. This starboard heel angle arises from the roll moment caused by the combination of the centripetal force and the hydrodynamic reaction forces acting at different vertical positions on the vessel. A controller has the dilemma of deciding which "way" to feed back the corrective rudder signal. Does the controller use port rudder to actuate a port roll or starboard? The answer is that it depends on the frequency of the correction that the controller needs to make. At high frequencies port rudder actuates a port roll while at low frequencies, port rudder actuates the exact opposite, a starboard roll. From a control designer's point of view, the NMP behaviour creates a limit on the forward loop gain of the controller (in order to keep the system stable), which leads to higher tracking errors. This is a fundamental limitation that is imposed on the RRS by the vessel dynamics.

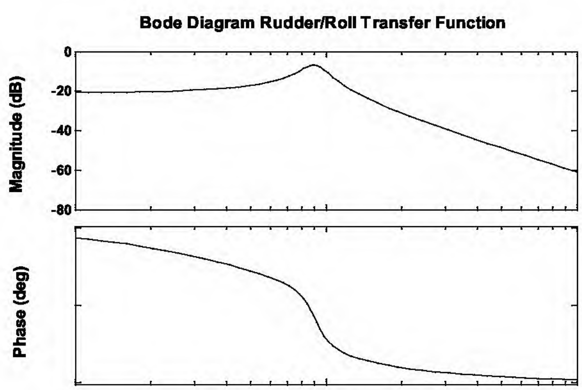


Figure 1: Magnitude and Phase transfer functions from rudder to roll for a typical vessel for one forward speed.

This discussion also hints at the problem of controlling both yaw and roll with the same actuator, since if we want to correct for a steady state roll using the rudder, we need to apply a steady state rudder angle, which leads to a steady turn (steadily increasing yaw). The complete coupling of yaw and roll at low frequency rules out the use of a single actuator, since it would be impossible to correct a constant roll trim offset without turning the vessel at the same time.

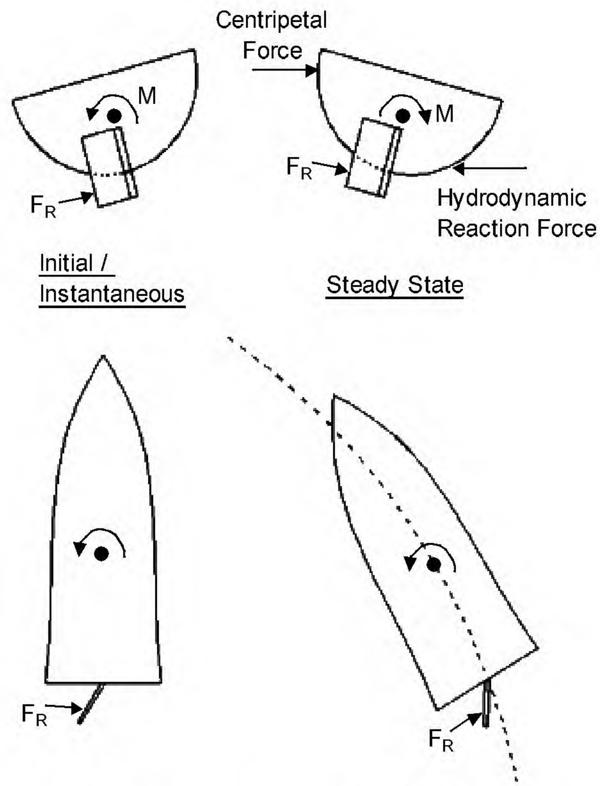
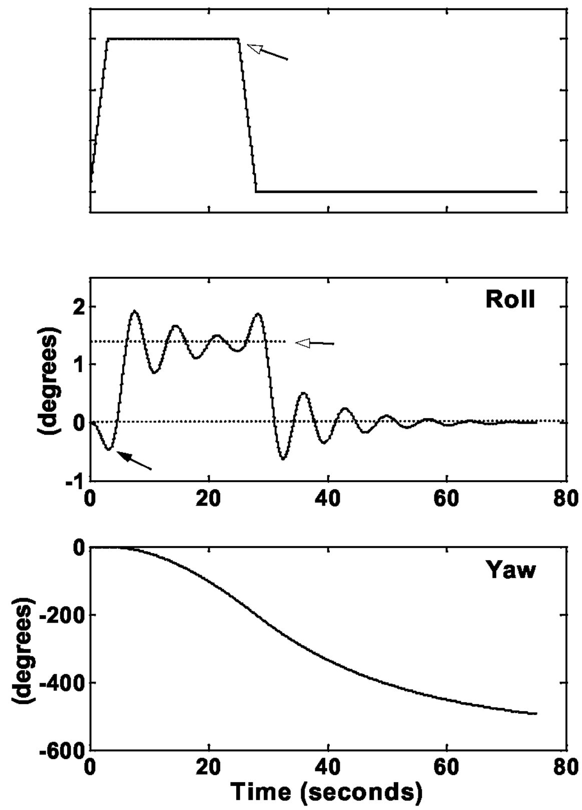


Figure 2: Roll Response to Rudder Movement

All RRS control systems deal with the coupling of the roll and yaw dynamics by separating the rudder corrections for each axis into separate frequency ranges (bands) of interest. This allows the yaw controller to ignore high frequency disturbances, while the roll controller can ignore low frequency disturbances. One simple way to do this is to set the rudder to react only to roll rate (instead of roll angle), which does not have a significant low frequency component. The rudder thereby becomes a device for roll damping. Figure 4 shows a block diagram of a simple RRS with proportional and derivative controller gains P_{YAW}, D_{YAW}, P_{ROLL}, D_{ROLL}. For the roll damping mode, $P_{ROLL} = 0$.

Examination of the magnitude response plot (for a typical vessel) indicates that there is a significant resonant peak for rudder to roll response, because of the combination of restoring forces due to buoyancy and the relatively low damping of the vessel on the roll axis. Increasing the damping of the vessel through use of the rudder effectively reduces the average magnitude of the roll angle.



deg./sec.). Slower rudder rates introduce a time lag in actuator response, which actually makes the NMP problem worse and the system harder to control. A fast-acting actuator is a necessity to effectively employ an RRS.

Are there any significant advantages in using a Z-drive to perform RRS, versus using a rudder? If we revisit the RRS limitations, NMP behaviour is a feature of ship dynamics and will still be there for a Z-drive vessel. The SIDO control structure is also still a factor, since angling the Z-drives affects both yaw and roll. Any differences between ZRS and RRS may lie in the differences between rudder and Z-drive characteristics as roll and yaw actuators. Z-drives do not have azimuth limits or suffer from stalling, and Z-drive units tend to have a higher slew rate than rudders. A ZRS system should therefore perform at least as well as an RRS and possibly better in some conditions.

4. NUMERICAL SHIP MOTION SIMULATION PROGRAM "MOTSIM"

MOTSIM is a non-linear time domain seakeeping code that simulates six degrees of freedom motion, with forward speed in any wave condition (Pawlowski & Bass, 1991). The ship's geometry is defined in terms of a sequence of sections, each of which is described by a set of panels. At each time step, the code determines the intersection of these panels with the waterline and redefines the paneling describing the ship's wetted surface. The pressure forces associated with the incident waves are then numerically integrated over this wetted

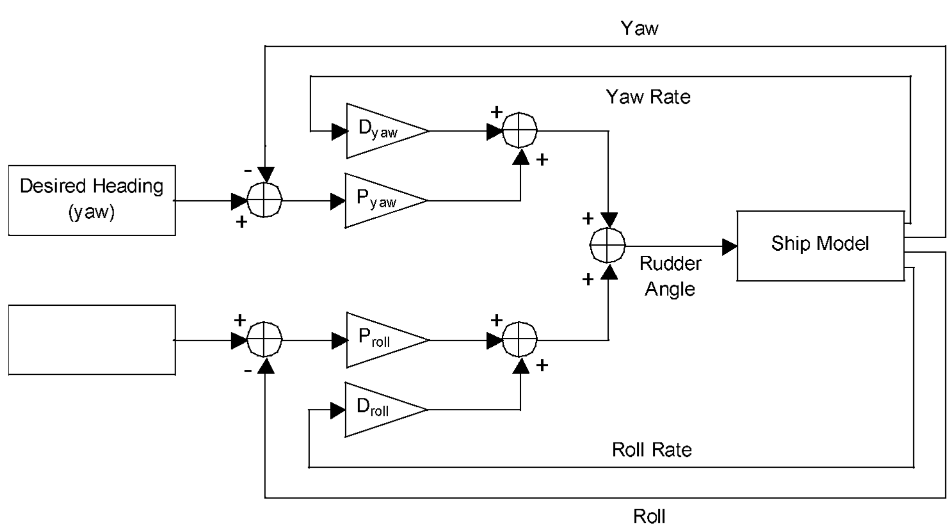


Figure 4: Block Diagram for RRS Control System

surface, using second order Gaussian quadrature. The normal velocity distribution associated with the velocity of the vessel and the incident wave particle velocity is averaged over each panel and then a least squares fitting of this distribution based on the wetted panels belonging to a particular section is made such that a unique decomposition of the modal velocities (surge, sway, heave and roll) is obtained that most closely satisfies the body boundary condition on the section. The use of the wetted surface to determine modal velocities serves as an approximation to a non-linear body boundary condition. The code allows for more general decompositions of the velocity distribution to be made using a higher number of non-standard modes. From this decomposition, the scattering forces and moments are determined for each section based on precalculated memory functions. The memory functions for each section are derived from added mass and damping coefficients from zero speed linear theory over a truncated semi-infinite frequency range. Their use allows for arbitrary frequency content in the scattering forces and moments. The added mass and damping coefficients can be either 2 or 3 dimensional. Corrections are made for forward speed.

Viscous effects associated with roll damping and manoeuvring are determined using semi-empirical formulae or experimentally determined coefficients. The total forces are then used in the non-linear equations of motion to determine the motions of the vessel.

5. NUMERICAL RESULTS

The behaviour of a vessel was predicted with and without Z-drive roll stabilization over a range of headings and wave periods using the program MOTSIM. An additional set of MOTSIM predictions was also performed with a conventional rudder/propeller propulsion system on the same vessel for comparison of the two roll reduction techniques.

Figure 5 shows the roll response predictions of the vessel moving at a steady speed of 8 knots for three headings (60, 90 and 120 degrees) over a range of wave periods (regular waves, wave height was 4.0 m) for the Z-drive propelled and rudder/propeller cases. As there was no active roll damping, the roll amplitudes were similar for the two propulsion types.

The next step was determining appropriate controller gains (P_{ROLL}, D_{ROLL}) to achieve roll reduction with the Z-drive units. These coefficients were manually tuned through a trial and error approach for each wave period and heading. This process involved running simulations over a range of gain values and then choosing the combination of P_{ROLL} & D_{ROLL} with the best roll response. It was found that the controller gains varied considerably depending on the encounter frequency of the waves. For example, in Figure 6, the roll amplitudes for sets of roll gain values are given for a single heading and wave period. In this case, the proportional gain had little influence on the roll amplitude. Increasing the derivative gain, however, resulted in improved roll response to a point, after which roll was intensified.

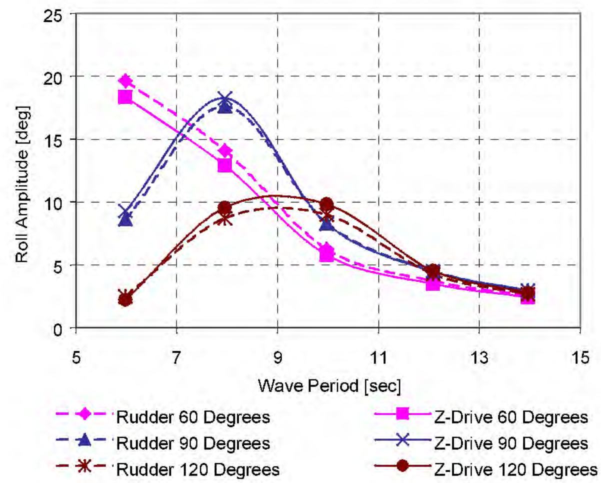


Figure 5: Roll Response – No Roll Damping

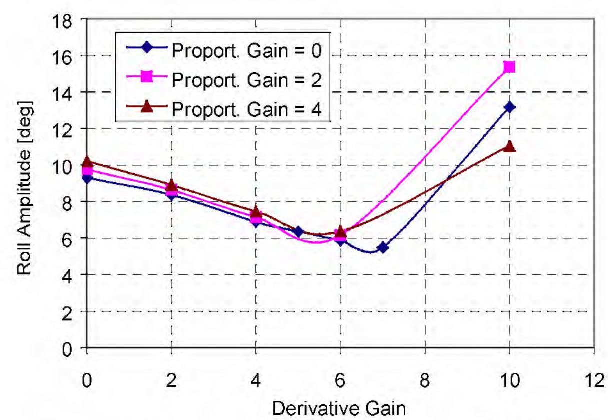


Figure 6: Heading = 90 deg., Wave Period = 6 sec.

This behaviour changed as the encounter frequency decreased. Shown in Figure 7 are the roll responses for another heading and wave period. For this encounter frequency, proportional gain replaces derivative gain as being the primary influence on roll reduction.

The results of the Z-drive roll stabilization predictions are given below in Figure 8. The best absolute improvement (10 degree reduction) was seen for the 90 degree heading in 8 second period regular waves and the best percentage improvement (65%) was found for the 120 heading in 10 second waves.

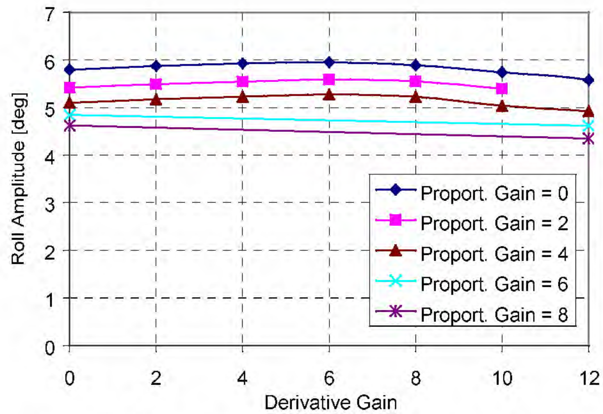


Figure 7: Heading = 60 deg., Wave Period = 10 sec.

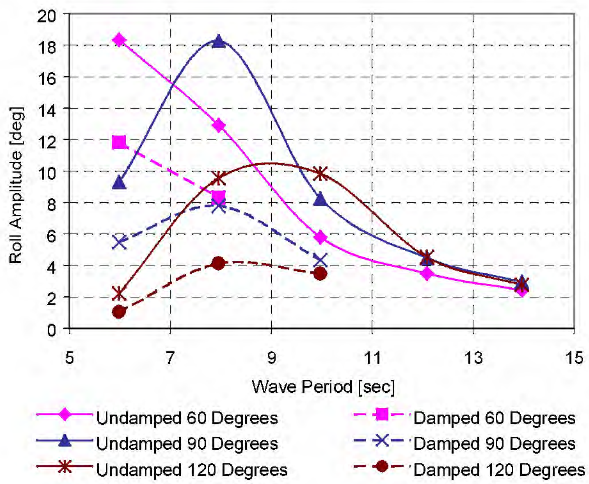


Figure 8: Z-drive Roll Response

The same set of predictions was also performed for the vessel with an equivalent rudder/propeller propulsion system replacing the Z-drives. The results from these simulations are shown in Figure 9.

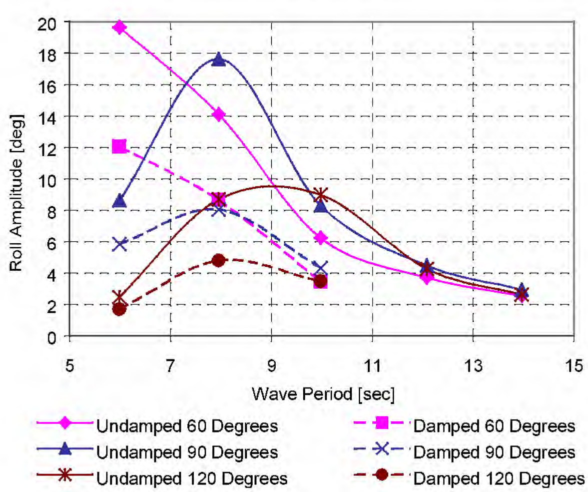


Figure 9: Rudder Roll Response

The roll responses when using ZRS and RRS were found to be essentially equivalent as shown in Figure 10.

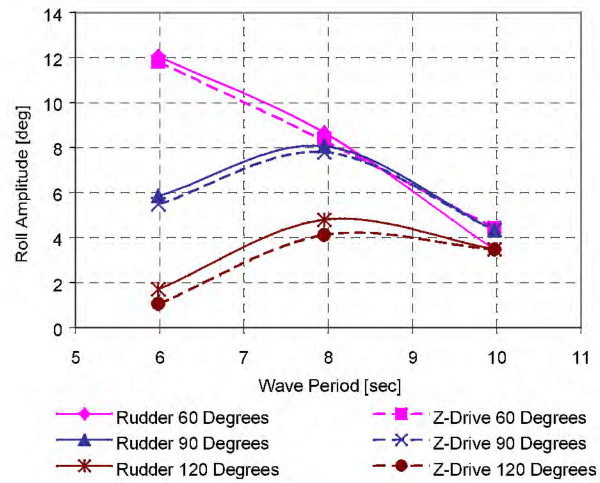


Figure 10: RRS vs. ZRS

The motions of the Z-drive and rudder during a typical run (60 degree heading, 8 second period waves) are given in Figure 11 and Figure 12. The rudder motions during active roll damping were sinusoidal in shape and just slightly out of phase with the roll motions. The Z-drive motion, which was nearly sinusoidal and slightly out of phase with roll, tended to swing towards one side more than the other. This was likely due to the influence of the course keeping and speed keeping controls compensating for loss of thrust when the Z-drives azimuth.

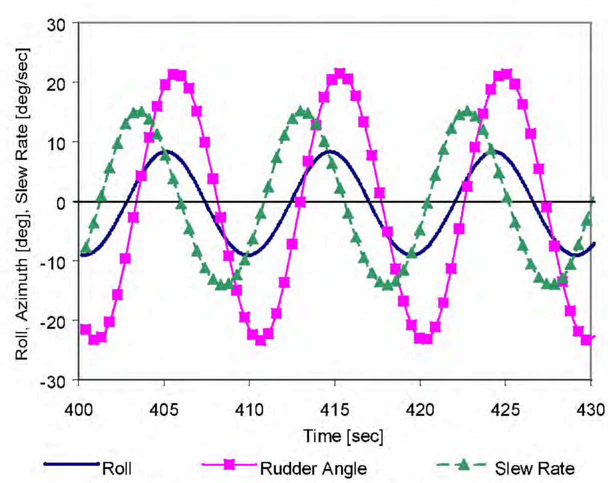


Figure 11: Rudder Motions

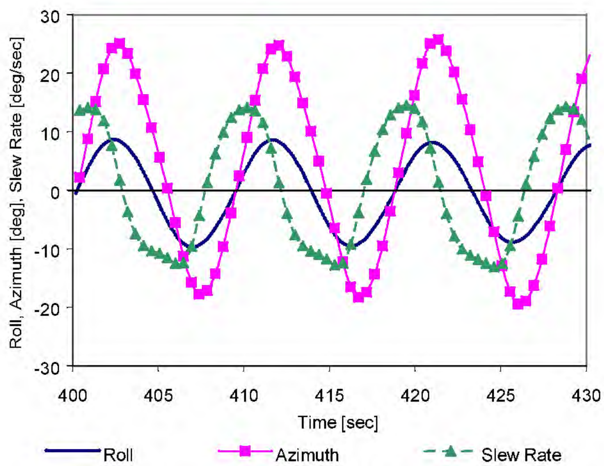


Figure 12: Z-drive Motions

The amplitudes of these motions are summarized below. In Figure 13, the swing amplitudes for the rudder and Z-drive for the various conditions is given. An upper limit of 35 degrees for the rudder is also shown (there are physical limits to rudder swing as well as stalling issues at high angles of attack). Only one condition at 60 degrees heading and 6-second waves predicted unrealizable rudder angles. Z-drives have the advantage of not being limited in this regard.

Figure 14 shows the slew rate amplitudes for the two cases. Both rudders and Z-drives have upper limits on how quickly they can turn (values for two vessels known to the authors are given in the figure). The RRS system, although theoretically comparable to the ZRS system, would be ineffective in practice without a substantial increase in the slew rate capacity of the rudder. The ZRS appears to be effective except in one condition at a 60 degree heading in 6 second waves.

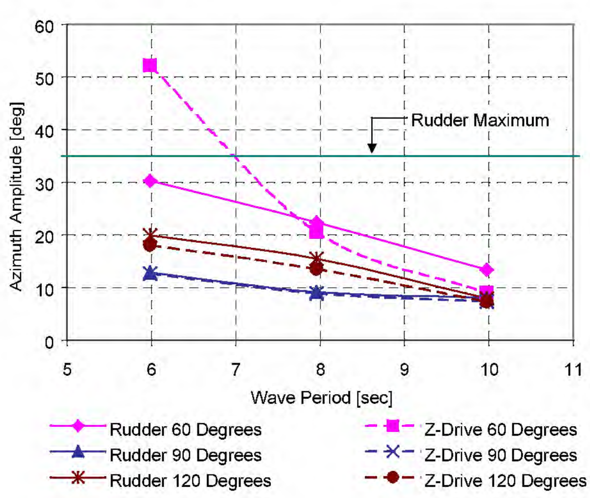


Figure 13: Azimuth Amplitudes

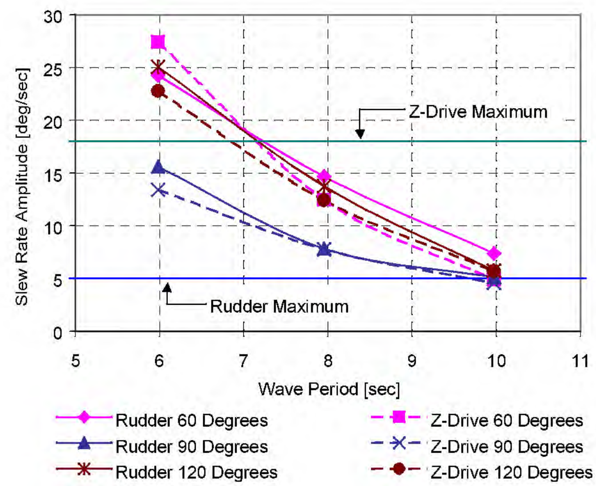


Figure 14: Slew Rate Amplitudes

5. CONCLUSIONS

Predictions of roll response for a vessel were conducted using the software MOTSIM. Active roll damping was then applied in the numerical model using Z-drives and compared with the results of rudder damping using an equivalent rudder/propeller propulsion system on the same vessel. It was found that both the Z-drive roll stabilization and rudder roll stabilization gave similar results for the headings and wave periods examined. Roll amplitudes were decreased between 23-65%, depending on the heading and wave period. Although rudder response during roll stabilization in regular waves was sinusoidal, the Z-drive response in the same conditions exhibited non-linear motions tending to swing more to one side than the other. This behaviour was likely due to the course-keeping and speed controls responding to the changing total forward thrust vector. Rudder angle amplitudes ranged from approximately 10-30 degrees. Z-drive azimuth amplitudes were comparable except for an anomalous value at the 60 degree heading case in 6 second waves. Rudder and Z-drive slew rates were similar. However, Z-drives typically have faster slew rate capabilities than rudders. For the two systems investigated here, the rudder (max. slew rate 5 deg./sec.) would only be effective in 10 second period waves or greater, while the Z-drive (max. slew rate 18 deg./sec.) could handle all but 60 and 120 degree headings in 6 second waves. Although more work is needed, these simulations demonstrate the potential of using Z-drive propulsion systems for roll stabilization.

6. FUTURE WORK

The method for applying the roll stabilizing force in the simulations was by azimuthing both thrusters quickly to port and starboard. Additional actuator scenarios are also possible with a vessel having twin Z-drives including:

- One Z-drive for forward speed, the other for roll and yaw correction,
- One Z-drive for yaw, one for roll,
- Differential thrust for yaw, combined with azimuthing for roll correction.

Other variations could be tried that use some combination of the above approaches, since some may be more effective than others depending on forward speed and environmental factors. Each of the actuator configurations may have some particular advantages, so future work should include quantifying these advantages. Numerical simulations may not show clear advantages/ disadvantages unless they take into account the actuator dynamics as well as the ship dynamics.

The effect of response lag of the Z-drives to the control system could also be investigated by the MOTSIM predictions, which may affect their ability to reduce roll motions. More sophisticated control systems could also be implemented in the numerical model that could account for response lags and which could better handle a broader range of conditions such as irregular waves.

Future work could include the modeling of thrust changes in the Z-drives due to the oblique flow experienced by the propeller during azimuthing. Experimental work has been done by Brandner & Renilson (1988), which examined the effect of azimuth angle on the net force supplied by a Z-drive at various forward speeds. This data could be incorporated into the numerical model to improve the prediction of the propulsor dynamics.

Physical model testing could be used to evaluate various ZRS configurations as well as validating MOTSIM's ability to predict ZRS performance. As the system only requires an additional control system, full scale trials on existing vessels could also be performed with relative ease.

7. REFERENCES

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