Use of Tunnel- and Azimuthing Thrusters for Roll Damping of Ships

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Abstract: This paper presents a novel technique of active roll damping in marine vessels by sole use of conventional thrusters. Many marine operations, such as crane operation and helicopter landing, should be carried out in small and steady roll motions. However, active roll damping devices such as fins and rudders lose their efficiency in low-speed conditions. This paper, by use of already installed thrusters, provides a new methodology for roll reduction by adjusting the shaft speed and pitch of the propellers. The numerical simulations, presented in the paper, shows promising results with significant roll damping.

Keywords: Roll Damping, Roll Control, Marine Vessels, Thruster Dynamics, Conventional Propellers, Particle Swarm Optimization.

1 Introduction

In numerous marine operations, roll-damping at zero speed is of extreme importance. Typical active roll reduction systems such as Rudder-Roll Damping (RRD) and Anti-Roll Fins, are not effective at zero speed. Anti-roll tanks work well at low and zero speed. However, not all the vessels are equipped with such devices and in certain vessels and operations, they cannot provide sufficient roll reduction. The use of thrusters for active roll reduction has already been proven feasible for cycloidal propellers Jürgens and Palm (2009). However, to the best of our knowledge, there is no report on the use of conventional propulsion systems, such as tunnel thrusters and azimuthing thrusters, for the purpose of roll reduction in marine vessels.

Reduction of roll motion is essential during many operations. Roll reduction can also be necessary to secure life at sea by reducing the hazard of capsizing, as well as lowering the risk of damaging cargo. Additionally, certain operations are constrained to have sufficient small roll amplitudes, e.g. helicopter landings and crane operations. In Norway the criteria for landing helicopters on small vessels requests for 2° or 3° in roll and pitch depending on the helicopter type, Helideck Certification Agency (2016). Furthermore, a workability analysis by van den Boom (2010) shows that the downtime for helicopter operations in the wintertime with good visibility varied between 70% and 90%. This implies that roll damping techniques could lead to a significant economic benefit for operators since helicopters could be utilized year round, and the vessel will not have to transit to shore mid-operation.

According to Weinblum and St.Denis (1950), Perez (2005), roll damping modifications of ships come in three different varieties of technology that uses three different ways of achieving roll damping: a) increase the damping, b) increase the inertia and c) reducing the exciting moment.

The primary focus and contribution of this paper is on the reduction of the net exciting moment and increase the damping using the propulsion system. The work presented in this paper is in an elementary stage and far from being complete; however the simulation results show promising effectiveness in roll reduction. The concept of reducing the exciting roll moment with a propulsion system was first proven to be efficient by Jürgens and Palm (2009). The major challenge in the reduction of the roll motion using the conventional thrusters compared to cycloidal propulsion units, is due to their limited ability to change the direction of thrust. Voith Schneider’s cycloidal propellers can change their direction of thrust nearly instantly, while the thruster dynamics of more conventional propellers is a function of the change of the shaft speed, pitching of the propeller blades, and the rate of change of azimuth angle.

The main drawback of actively changing the shaft speed and, propeller pitch and azimuth angle for roll reduction are the considerable wear and tear on the propulsion system. However, “Roll Reduction Mode” might be executed only during particular critical operations that are constrained to low roll motions. Thus the operation time of this control system can be of a minimal nature.

The structure of the paper is as follows. Thruster dynamics are covered in Section 2. Section 3, briefly summarizes the controller structure and the parameter tuning adopted in
the paper. Numerical simulations are reported in Section 4. Conclusions and future works are summarized in Section 5.

In order to make the case realistic, an existing vessel has been used. The main particulars for the case vessel are listed in Table 1.

### Table 1. Main particulars for case vessel

| Ship       | LOA [m] | B [m] | D [m] | T_N4 [s] |
|------------|---------|-------|-------|----------|
| Length overall | 99      | 6     | 12    |          |
| Breadth moulded |        | 21    |       |          |
| Design draught |        | 6     |       |          |

2 Thruster Modeling

The case vessel is equipped with two thruster pairs; two Azipull thrusters in the stern and two bow thrusters in the bow. The main parameters for the thrusters are summarized in Table 2.

### Table 2. Main parameters for the propulsion system.

|          | Azimuth | Bow |
|----------|---------|-----|
| Power    | PD [kW] | 2200 | 970 |
| D [m]    | 3       | 2.2  |
| Pitching | PT [s]  | 15   | 15  |

2.1 4-Quadrant Model

Even though the current paper’s main attention is on the roll reduction at zero-speed, it is not sufficient to model the thrust by bollard pull condition due to the fact that the ship is rolling, and thereby the inflow velocity to the thrusters is varying. Furthermore, roll reduction using the thrusters is not a conventional operation where the propellers are working in only one direction, e.g. positive advance ratio. Because of the zero-speed case with roll motion, the motions will introduce oscillating advance speeds to the thrusters as they are pointing in the direction of the roll motion. Thus leading to both positive and negative advance ratios. Standard open water diagram can no longer address the problem sufficiently; for further discussions on this, see Smogeli (2006), Miniovich (1960), and van Lammeren et al. (1969). In this report, the Wageningen B-Series propellers are used to describe the 4-quadrants. The quadrants are separated by the angle of attack $\beta$, which is described by the ambient water velocity ($V_a$), the tangential water velocity ($V_t$), the propeller rotation rate ($n$) and the propeller diameter ($D$) (see Table 2) as

$$\beta = \arctan\left(\frac{V_a}{V_t}\right) = \arctan\left(\frac{V_a}{0.7\pi n D}\right), \quad (1)$$

The quadrants as defined by Carlton (1994) are described in Table 3.

### Table 3. The 4-quadrants

| Quadrant | Condition | $V_a$ | $n$ |
|----------|-----------|------|-----|
| 1st      | $0^\circ \leq \beta \leq 90^\circ$ | $V_a > 0$ | $n > 0$ |
| 2nd      | $90^\circ < \beta \leq 180^\circ$ | $V_a > 0$ | $n < 0$ |
| 3rd      | $180^\circ < \beta \leq 270^\circ$ | $V_a < 0$ | $n < 0$ |
| 4th      | $270^\circ < \beta \leq 360^\circ$ | $V_a < 0$ | $n > 0$ |

During the proposed roll reduction operation in zero-speed, only the 1st and 4th quadrant are of concern since the shaft speed direction is positive. Thus, the relevant $\beta$ values are in the interval $-90^\circ \leq \beta \leq 90^\circ$. The non-dimensional thrust coefficient for the 4-quadrant model is defined as

$$C_T = \frac{T_a}{n \rho (V_a^2 + (0.7\pi n D)^2) D^2}. \quad (2)$$

2.2 Model Representation

The open water characteristics are determined experimentally, and in order to use these results in simulations, a further modification must be introduced to avoid the non-continuous behavior of the experimental values.

The thrust- and torque coefficients for some propellers were described by van Lammeren et al. (1969) using a 20th order Fourier series using two coefficients for the thrust ($A_T$ and $B_T$) and two for the torque ($A_Q$ and $B_Q$). The thrust and torque representations can then be calculated using:

$$C_T(\beta) = \sum_{k=0}^{20} (A_T(k) \cos(\beta k) + B_T(k) \sin(\beta k)), \quad (3a)$$

$$C_Q(\beta) = \sum_{k=0}^{20} (A_Q(k) \cos(\beta k) + B_Q(k) \sin(\beta k)). \quad (3b)$$

Fig. 1 can depict this, where the 1st and 4th quadrants are plotted using equations (3). The coefficients used are found from the Wageningen B4-70 which is tabulated in van Lammeren et al. (1969, Table 7) and is discussed thoroughly in Smogeli (2006).

![Fig. 1. $C_T$ and $C_Q$ 1st and 4th quadrant from the 20th Fourier series, van Lammeren et al. (1969).](image)
Pitch ratio \( \frac{P}{D} \), can be found by using (2) and (4) and setting the advance velocity equal to zero.

\[
T_0 = \left[10^6 \rho \pi n_p^2\right]^\frac{1}{3} \cdot \left[D^2 P^2 \right] \frac{1}{3}.
\]  

(4)

The 4-quadrant bollard pull thrust \( (T_0) \) and the corresponding thrust coefficient can be found for the propellers using Table 2. Furthermore, the pump efficiency \( (\eta_p) \) are set to 0.5 for open propellers, i.e. Azimuth thrusters, and 0.7 for ducted propellers, i.e. bow thrusters (Steen, 2014, p.284).

Table 4. Bollard pull and 4-quadrant thrust coefficient calculations.  

|                  | Azimull Thruster | Bow Thruster |
|------------------|------------------|-------------|
| Pump efficiency  | \( \eta_p \)     | 0.5         |
| Thrust coefficient | \( C_T(0) \)     | 0.145       |
| Bollard pull     | \( T_0 \)        | 327         |
| Thrust coefficient | \( C_T(0) \)     | 0.196       |

2.3 Thruster Dynamics

Both the Azimuth and bow thrusters have the ability to regulate propeller pitch and shaft speed. Both the bow and the Azimuth thrusters have pitching times (0-100\%) equal to 7.5 seconds, while the shaft speeds require 10 seconds to reach to its maximum speed. The thrust was found to be increasing linearly with the pitch, and this was calculated by changing the pitch angle for Wageningen B-series Propellers Open Water characteristics while the advance ratio was set to zero, i.e. bollard pull. This linearity is depicted in Fig. 2.

![Fig. 2. Thrust coefficient as a function of the propeller pitch. With regression line, R=99 %](image)

The thrust increases with the square of the shaft speed because the open water equation follows

\[
K_T = \frac{T_0}{\rho \cdot D^2 \cdot n^2}.
\]

(5)

Thrust can be controlled by pitch, shaft speed or a combination of the two. In Fig. 3, representative time series of thrust controlled by only pitch angle, only shaft speed, and a combination of both pitch angle and shaft speed are presented.

![Fig. 3. Red: Thrust with respect to time for pitch-control. Blue: Shaft speed control. Green: A combination between pitch and shaft speed control.](image)

Fig. 3 illustrates that the reaction times are relatively slow if one wants to vary the thrust between 0-100\% thrust by sole use of pitch or shaft speed. To overcome this problem, it is suggested to regulate the thrust by combining pitch and shaft speed control, because it has the steepest slope. Furthermore, constrain the minimum thrust to a certain limit, e.g. operating in the range 30-100\% thrust. Table 5 presents the reaction time for different minimum thrust limits when using the combination of pitch and shaft speed to control thrust.

Table 5. Thruster reaction time with respect to minimum thrust limit.

| Minimum thrust limit [%] | 20  | 30  | 40  | 50  | 60  |
|--------------------------|-----|-----|-----|-----|-----|
| Reaction time [s]        | 3.76| 2.99| 2.38| 1.86| 1.41|

3 Control

The controller that is exploited in the current paper is of a nonlinear Proportional Derivative (PD) controller type, in the form of

\[
\tau_{PD} = -K_P \cdot \text{sign}(\dot{n}_i) \sqrt{\frac{|\dot{n}_i|}{c}} - K_D \cdot \ddot{n}_i.
\]

(6)

The nonlinear square root term is added because the contribution from the thrusters should be equally large for all roll rates \( \dot{n}_i \). By applying the square root term, the term \( \sqrt{\frac{|\dot{n}_i|}{c}} \) will be decreased for \( |\dot{n}_i|/c > 1 \), and increased for \( |\dot{n}_i|/c < 1 \), where \( c \) is a tuning parameter. If linear control would be utilized and the \( K_P \) term would be large, the system would work well for lower roll rates, but saturate the shaft speed for too long duration during larger roll rates. For lower gains, the system would work well for large roll rates, but the shaft speed would not be fully utilized for lower roll rates.

3.1 Tuning and Optimization of gains

The tuning of the nonlinear PD-controller can be done by varying the gains \( P, D, \) and \( c \). An optimization algorithm is proposed to find the optimal gains.
A particle swarm optimization (PSO), see Kennedy and Eberhart (1995), algorithm was chosen to identify the most suitable gains and thruster limits.

The algorithm assigns each particle a random position in the search space (x) and a random velocity (v). The positions and velocities are updated for each iteration (k) for all the i-th particle using the following equations

\[
x_{i,k+1} = x_{i,k} + v_{i,k+1},
\]

\[
v_{i,k+1} = \omega v_{i,k} + \phi_p r_p (p_{i,k} - x_{i,k}) + \phi_r r_g (p_{g,k} - x_{i,k}),
\]

where \( \omega \) is a so-called inertia parameter, which scales the previous particle velocity. Additionally, this parameter is dynamic, meaning that it will narrow towards the optimal solution through the optimization process. The parameters \( \phi_p \) and \( \phi_r \) denote user set scaling parameters which define how much the particles are dependent on the swarm and themselves. Furthermore, \( p_{i,k} \) represents the i-th particle and \( p_{g,k} \) is the particle containing the most optimal solution for the iteration \( k \). This particle will redirect the swarm towards its location, Ehlers (2012). The \( r_p \) and \( r_g \) represents random number in the interval \( r_p, r_g \in [0,1] \).

The velocity components in (8) can be broken down into two categories, namely the cognitive velocity component (CVC) and the social velocity component (SVC). The former represents the difference between the i-th particle and the currently best-known particle in the k-th iteration. The latter represents the difference between the i-th particle and the global best known, i.e. the best through the entire optimization process. These results are then used as an input to the objective function, which is updated accordingly. The optimization process ends when the prescribed number of iterations is reached. The PSO implementation used in the current paper is written in MATLAB, and is a modified version of Ehlers (2012) and Jalkanen (2006).

4 Simulation results

The simulation environment used is a modified version of Perez and Fossen (2000). The Toolbox uses ShipX VERES output to compute retardation functions. For more information see Perez and Fossen (2009).

To see the effect of the roll damping system using thrusters, is it necessary to carry out different seakeeping trials related to roll motion. In what follows, three sets of simulations are presented. First decay tests to find the damping ratio. Furthermore, forced oscillation tests are conducted to study which roll amplitudes the system can damp effectively. Lastly, irregular wave trials are examined and compared with the standards for helicopter landing, Helideck Certification Agency (2016).

4.1 Decay Trials

A series of (numerical) decay tests are carried out with the purpose of sensitivity study. Decay tests were chosen because they illustrate the damping of a dynamic system. During measurements of damping in decay tests, it is common practice to calculate the logarithmic decrement (\( \Lambda \)). The logarithmic decrement is calculated using two succeeding amplitudes (\( X_i \)) where \( i \) describes each succeeding amplitude:

\[
\Lambda = \ln\left( \frac{X_i}{X_{i+1}} \right).
\]

Then, the damping ratio \( \xi \) is described by the logarithmic decrement as:

\[
\xi = \frac{\Lambda}{\sqrt{(2\pi)^2 + \Lambda^2}}.
\]

The results from the decay tests are depicted below in Fig. 4. The decay trial without roll control resulted in an average damping ratio equal to 0.0499. When roll control is activated the damping ratio is increased to 0.1145, which is 2.3 times the original damping ratio.

![Fig. 4. Results from decay test comparison.](image)

4.2 Forced Oscillations

Forced motion is a test used to see how the vessel responds to different excitation forces and moments. One can look at the system as if a lever is exciting the vessel with a given force amplitude and frequency, thus exposing it to harmonic motions. It was of interest to conduct these trials to see how large the excitation moment the thrusters can counteract before the damping contribution becomes insignificant. This was measured by exciting the vessel until it reached a constant roll motion. Furthermore, the damping contribution could be calculated by looking at the difference of the maximum amplitude with and without roll control, both cases were exposed equal force amplitude and frequency. These tests were carried out for roll amplitudes \( \eta_{14} \in [1°, 35°] \). The results are depicted in Fig. 5. It should be noted that the control gains were the same for all the trials.

![Fig. 5. Damping with the respect to undamped forced roll motion.](image)
4.3 Irregular Waves

In order to attain more realistic simulation scenarios, in what follows, a series of numerical simulations are presented where the vessel is excited by irregular waves. Since our simulations are carried out for a beam sea case, only long crested waves are used. The irregular waves were implemented according to the 17th ITTC recommended JONSWAP (Joint North Sea Wave Project) spectrum. The spectrum used have peak frequency selected as the natural roll period (Tp = 12 s), with a significant wave height equal to 1 and 3 meters, and γ is equal to 3.3.

Fig. 6 illustrates how the roll motions respond when the vessel is excited by significant wave height (Hs) equal to 1 meter. The results show that the motions are damped well.

\[ \eta_4 [\text{deg}] \]
\[ f(\eta_4) \]
\[ \text{Without Roll Control} \]
\[ \text{With Roll Control} \]

Fig. 6. Roll motions comparison. Excited with wave characteristics Hs = 1 m and Tp = 12 s.

Fig. 7 shows the distribution of the roll amplitudes for a sea state with significant wave height equal to 1 meter (simulations were carried out for to 20 minutes). The Weibull distribution is used to represent the roll peaks, Fig. 8 shows that this representation is a good fit for the roll peaks. The results can be used in computing the operability of helicopter landing, according to Helideck Certification Agency (2016), with and without roll control.

\[ \text{Fig. 7. Weibull distributions of the roll peaks in a sea state with Hs = 1 m and Tp = 12 s.} \]

From the table, it is clear that the regime that cover helicopter operations are increased from 13.2% to 81.4% for \( \eta_{4\text{crit}} = 2^\circ \) and from 32.4% to 94.5% for \( \eta_{4\text{crit}} = 3^\circ \), which is a significant increase. Hence, the operability for helicopter operations on a vessel can be much improved for this sea state.

These results can also be studied from another point of view by demanding that the probability of exceeding the criteria should be below a certain percentage, e.g. 5%, and then find the corresponding Hs. The results from this study are presented in Table 7.

\[ \text{Table 7. Significant wave height when the probability of exceeding roll criteria is 5%.} \]

| Roll control | Off | On | Improvement |
|--------------|-----|----|-------------|
| Standard deviation | \( \sigma \) | 1.64° | 0.92° | 43.9 % |
| Root mean square | RMS | 4.19° | 1.52° | 63.7 % |
| Average amplitude | \( A_{\text{avg}} \) | 3.86° | 1.22° | 68.5 % |
| Maximum amplitude | \( A_{\text{max}} \) | 7.94° | 4.67° | 41.2 % |
| \( P(\eta_4 > 2) \) | 86.8 % | 18.6 % | 68.2 % |
| \( P(\eta_4 > 3) \) | 67.6 % | 5.6 % | 62.0 % |

An identical approach was used for a sea state with significant wave height equal to 3 meters, with the same peak period. The resulting roll motions are illustrated in Fig. 9, and the results are summarized in Table 8.
Table 8. Results from sea state Hs=3 m, Tp=12 s, T = 20 min.

| Roll control         | Off | On  | Improvement |
|----------------------|-----|-----|-------------|
| Standard deviation   | σ   |     | 14.3 %      |
| Root mean square     | RMS | 12.56° | 8.62° | 31.3 %      |
| Average amplitude    | A_{avg} | 11.56° | 7.53° | 34.8 %      |
| Maximum amplitude    | A_{max} | 23.77° | 19.7° | 17.0 %      |
| P(\eta > 2)          | 99.3 % | 93.4 % | 5.9 %       |
| P(\eta > 3)          | 98.2 % | 86.5 % | 11.7 %      |

By comparing the results from Table 6 and 8, one can clearly see that the relative roll reduction is smaller in Hs = 3 m than in Hs = 1 m. This is because the thrusters do not have sufficient capacity to counteract the large roll excitation moments occurring in Hs = 3 m.

5 Conclusion

This paper has studied the feasibility of using conventional thrusters to damp roll motions of vessels actively. Since the thrusters are fairly slow to build the thrust from 0-100%, it is found that more effective roll reduction is obtained by varying the thrust between a non-zero lower limit and maximum, e.g. 20% and 100%. The trade-off between a lower thrust limit and reaction time was found by optimizing the thruster reaction time with the control gains, using a PSO algorithm. Several typical trials were conducted in order to see to what degree the roll motions would be damped for different conditions using the proposed anti-roll system. With the help of numerical decay tests, it was shown that the proposed active roll reduction more than doubles the damping ratio. Furthermore, a series of numerically simulated forced oscillation experiments revealed that more than 50% damping could be introduced to the system when the roll motion is below 15°. Finally, two different irregular wave spectra were used to excite the vessel. They were both long-crested beam waves with significant wave heights of 1 and 3 meters, both with peak period equal to the natural roll period. The results were compared to the Norwegian helicopter landing operation criteria for roll amplitudes. The sea state with significant wave height of 1 meter showed promising results. The probability of experiencing roll amplitudes below the helicopter landing criteria was increased with 62% and 68%. Furthermore, the statistical roll properties were reduced somewhere between 40-70% when the proposed active roll damping system was used. For the higher sea state, the probability of experiencing roll amplitudes below the helicopter landing criteria and the reduction of the statistical roll properties were significantly lower due to the fact that the wave exciting roll was so big that the thruster could not provide a sufficient counteracting moment. Based on the results, it can be concluded that the system works very well for moderate sea states.

A series of model scale tests are planned in near future for verifying the effectiveness of the proposed methodology in roll reduction. Future work will also include augmenting the proposed system in a dynamic positioning system, where more advanced controller should be designed.

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