A COMFORT ANALYSIS OF AN 86M YACHT FITTED WITH FIN STABILIZERS VS. MAGNUS-EFFECT ROTORS

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SUMMARY
Comfort on-board is of utmost importance in the yacht industry, and roll stabilization plays a crucial role in achieving it. In this paper, two types of roll stabilizers are presented and analyzed: fin stabilizers, and Magnus-effect rotor stabilizers. To investigate the relative merits of these two stabilizer concepts, Quantum carried out model tests at MARIN in December 2015. The two pairs of stabilizers were separately fitted to a scaled model of an 86m yacht, and comparative tests were performed in calm water and irregular waves at various ship speeds (including zero speed), headings, and sea conditions. Results from these tests are presented and discussed in this paper, with specific attention to the influence of the performance on perceived comfort on-board.

1. INTRODUCTION
Among the different types of roll stabilizers for ships, stabilizer fins are the most common and have seen widespread use since the early 1900s. Several alternative stabilizer solutions exist such as gyroscopes, anti-roll tanks, and moving weight systems (Smith and Thomas 1990) but these have mainly found use in niche applications. Yet another stabilizer concept makes use of Magnus effect rotors. Here, use is made of the lift force generated by a spinning cylinder that’s moving through the water. The lift force is modified by varying the spin speed and spin direction. Since the concept involves lift forces, just as fin stabilizers do, there are many similarities in the characteristics of fins and Magnus rotors. However, there are also a number of differences that must be taken into account when selecting the optimal stabilizer system for a vessel. From literature, simulations, and calculations much was already known about Magnus rotors, but a need was felt for verification and a comparison of both systems, hence the present investigation was born.

2. FINS AND MAGNUS ROTORS
The Magnus effect is the phenomenon in which a lift force is generated on a rotating cylinder or sphere placed in a cross flow. Similar to the lifting theory of a foil, the pressure differential across the body is what causes the lift force. For a foil, this pressure differential is created by its asymmetrical shape or its angle of attack, and for a cylinder it is achieved by spinning the body. This concept is illustrated below in Figure 1.

![Figure 1 Lift forces generated by a pressure differential](image-url)
The lift forces of both fins and rotors can be approximated by the well-known equation for lift:

\[ F_L = \frac{1}{2} \cdot \rho \cdot V^2 \cdot A \cdot C_L \]  

with:
- \( \rho \) fluid density
- \( A \) projected area
- \( C_L \) lift coefficient
- \( V \) flow velocity

The lift coefficient of a fin is dependent on the angle of attack between the fin and undisturbed flow; Figure 2 gives an example of the lift coefficient of a low aspect ratio stabilizer fin. For a rotor, the lift coefficient is dependent on the “k-factor” which is defined as the ratio of the rotor’s circumferential speed to the flow velocity. The lift coefficient of a rotor increases over the range \( k=0 \) to \( k=3 \), and for \( k>3 \) it is approximately constant. In general, the maximum lift coefficient of a rotor is roughly equal to its aspect ratio (AR=length/diameter). Figure 3 shows an example of the lift coefficient of a rotor (Sosa 2014) with an aspect ratio of 5.

![Figure 2 Lift coefficient of low aspect ratio fin (AR=0.4)](image1)

![Figure 3 Lift coefficient of a Magnus rotor (AR=5)](image2)

Apparent from the lift coefficient plots is the fact that a rotor has a much higher maximum lift coefficient than a fin. In the present tests the rotor aspect ratio is 7, resulting in a maximum lift coefficient of approximately 7 for \( k=3 \). In comparison, the fin’s maximum lift coefficient is roughly 1.1. So to achieve similar lift forces, the fin area must be much larger than the rotor area. The product of the area and lift coefficient, \( A \cdot C_L \), is a figure of merit: the larger the product, the larger the lift force at a given ship speed. For the tested vessel the fin area was 7.5 \( m^2 \); the rotor had a projected area of 1.48 \( m^2 \). These sizes where chosen such that at 12 knots both systems had identical performance. Note that at high speeds the maximum lift coefficient of both rotors and fins cannot be reached because the fin cannot and should not be moved to the required large fin angles, and the rotor cannot spin fast enough to keep up the lift coefficient. But at medium and low speeds the maximum lift coefficients can be reached.

Calculating the \( A \cdot C_L \) for the fin and the rotor gives 8.25 for the fins and 10.4 for the rotors. So, in medium and low speed conditions the rotors should have better performance. At higher speeds the loss of lift coefficient of the rotor goes faster than that of the fins, so at higher speeds the fins should show better performance. The performance cross-over point obviously depends on the fin and rotor sizing and in the present case it is 12 knots.
2.1 Operational Principles: Underway vs. Zero Speed

For the fins and rotors to create the lift force as presented in Equation 1, flow past the stabilizer is required. While the vessel is underway this is achieved easily, however, at zero speed this is not the case. To remedy this, in zero speed the fins are not used as a conventional lifting body but instead are used as “paddles”. By moving the fins quickly and at precisely the right time, the paddle force that they generate can reduce the roll of the vessel (Ooms 2002, Dallinga 1999).

The operational concept behind the rotors is different from that of the fins. To use rotors in zero speed, a relative flow velocity over the rotor is introduced by swinging the rotors fore and aft. The rotor is kept spinning at a constant rate and the required stabilizing lift force is generated by varying the speed and direction of the swing motion. The swing angle can be varied between -60° and 60° and is continuously adjusted. While the vessel is underway, however, the rotors are fixed perpendicular to the vessel, and the lift force is generated by varying the speed and direction of rotation.

2.2 Comparison

Fins and rotors both have their individual advantages and disadvantages which should be considered when selecting the proper stabilizer solution for a specific vessel. An abbreviated list of pros and cons is provided in Table 1:

<table>
<thead>
<tr>
<th>Pros and cons of Magnus rotors and stabilizer fins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotors</td>
</tr>
<tr>
<td>High lift coefficient</td>
</tr>
<tr>
<td>Longer lever arm for stabilization moment</td>
</tr>
<tr>
<td>Retracted when not in use</td>
</tr>
<tr>
<td>Less drag when not in use</td>
</tr>
<tr>
<td>Better underwater performance at low vessel speeds</td>
</tr>
<tr>
<td>Often better performance at zero speed</td>
</tr>
<tr>
<td>Less interference effects in 4-stabilizer systems</td>
</tr>
<tr>
<td>More flexibility in placement on hull</td>
</tr>
<tr>
<td>Stick outside of maximum beam</td>
</tr>
<tr>
<td>Not usable at speeds higher than approx. 14kn</td>
</tr>
<tr>
<td>Higher power consumption</td>
</tr>
<tr>
<td>More drag than fins when in use</td>
</tr>
<tr>
<td>More complex mechanical system</td>
</tr>
<tr>
<td>Does not provide passive damping</td>
</tr>
<tr>
<td>More bilge keel area may be needed</td>
</tr>
<tr>
<td>Fins</td>
</tr>
<tr>
<td>Low lift coefficient</td>
</tr>
<tr>
<td>Shorter lever arm for stabilization moment</td>
</tr>
<tr>
<td>Always deployed</td>
</tr>
<tr>
<td>More drag when not in use</td>
</tr>
<tr>
<td>Less performance at low vessel speeds</td>
</tr>
<tr>
<td>Often less performance at zero speed</td>
</tr>
<tr>
<td>More interference effects in 4-stabilizer systems</td>
</tr>
<tr>
<td>Placement options limited by hull form</td>
</tr>
<tr>
<td>Stay within maximum beam</td>
</tr>
<tr>
<td>Very effective at high vessel speeds</td>
</tr>
<tr>
<td>Lower power consumption</td>
</tr>
<tr>
<td>Less drag than rotors when in use</td>
</tr>
<tr>
<td>Relatively simply mechanical system</td>
</tr>
<tr>
<td>Provides roll damping when not in use</td>
</tr>
<tr>
<td>Size of bilge keels can be reduced</td>
</tr>
</tbody>
</table>

3. ANALYZING VESSEL COMFORT

Due to the subjective nature of passenger comfort, quantifying it presents a unique challenge. Studies into comfort and seasickness indicate that comfort on-board is dependent on a range of different factors, including but not limited to:

1. Vertical and transverse accelerations resulting from heave, roll, and pitch
2. Discrepancies between the experienced accelerations and visual information
3. The direction of the resultant vector between the vertical and transverse accelerations
4. The presence of high-frequency vibrations
5. The frequency of the vessel motions (human sensitivity is highest around 0.2 Hz)
6. Individual characteristics such as: age, gender, habituation, seasickness history, duration of exposure
7. The presence or high “jerk” motions (rate of change of acceleration)

Based on research carried out in the EU Compass Project G3RD-CT-2002-00809 (Turan 2006), an Illness Rating was formulated based on items 1 and 2 and 5 in the above list. The MARIN Comfort Rating is an inversion of the Illness Rating (Gaillard et al 2010). The scale for the comfort and illness ratings is presented below in Table 2. On the comfort scale, MARIN recommends a lower limit for passengers on cruise liners of 90% and a lower limit for crew of 80%.

<table>
<thead>
<tr>
<th>Comfort Rating</th>
<th>Illness Rating</th>
<th>Passenger Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-90</td>
<td>0-10</td>
<td>Very comfortable</td>
</tr>
<tr>
<td>90-85</td>
<td>10-15</td>
<td>Comfortable</td>
</tr>
<tr>
<td>85-75</td>
<td>15-25</td>
<td>Alright</td>
</tr>
<tr>
<td>75-50</td>
<td>25-50</td>
<td>Slightly unwell</td>
</tr>
<tr>
<td>50-25</td>
<td>50-75</td>
<td>Quite ill</td>
</tr>
<tr>
<td>25-0</td>
<td>75-100</td>
<td>Absolutely dreadful</td>
</tr>
</tbody>
</table>

4. MODEL TEST TECHNIQUES

4.1 Testing Facility & Setup
The tests were carried out in the Seakeeping and Maneuvering Basin at MARIN. The dimensions of this basin in length, width, and depth are 170 x 40 x 5 m, respectively. The basin’s wave maker is capable of generating irregular and regular waves from any direction by way of the 331 wave flaps that run along two adjacent sides of the basin. A model tested in the SMB can be either captive or free-sailing, and the carriage can move along the length and width of the basin to tow or follow a model at a maximum speed of 6m/s.

In the present test setup, the model was self-propelled and free-sailing. An auto-pilot controlled the model’s rudders to maintain the correct heading with respect to the waves. Servo systems were fitted to control the movement of the fins and rotors. Additionally, sensors were fitted to the model to measure the following signals:

- Fin angle
- Rotor swing angle and spin rpm
- Six degrees of freedom motions
- Accelerations in x, y, and z
- Ship speed
- Propeller thrust, torque and rpm
4.2 Vessel
The vessel tested was an 86m yacht. The hull lines were developed by MARIN to represent a motor yacht with a hull form and design features typical of a yacht of this size. The model was constructed out of wood at a model scale of 1:14.241. The main characteristics of the vessel are provided below in Table 3. The vessel was tested at one loading condition which was representative of full-load.

Table 3 Main vessel characteristics

<table>
<thead>
<tr>
<th>Vessel Particulars</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LOA</td>
<td>86.1 m</td>
</tr>
<tr>
<td>LWL</td>
<td>75.3 m</td>
</tr>
<tr>
<td>Beam (moulded)</td>
<td>12.4 m</td>
</tr>
<tr>
<td>Beam (waterline)</td>
<td>12.4 m</td>
</tr>
<tr>
<td>Draught (1/1)</td>
<td>3.3 m</td>
</tr>
<tr>
<td>Displacement (1/1)</td>
<td>1729 MT</td>
</tr>
<tr>
<td>GM (1/1)</td>
<td>1.14 m</td>
</tr>
<tr>
<td>KM</td>
<td>6.75 m</td>
</tr>
<tr>
<td>Roll Period</td>
<td>10 sec</td>
</tr>
<tr>
<td>Speed (cruise)</td>
<td>14 kn</td>
</tr>
</tbody>
</table>

Figure 4 shows the plan view of the vessel. For illustration purposes, both the fins and rotors are shown on the hull. However, tests were only carried out with one system or the other, never with both systems simultaneously.

Figure 4 Hull fitted with fins and rotors
4.3 Stabilizer Fins
The stabilizer fins fitted to the vessel were Quantum’s low-aspect ratio XT fins. The XT foil is a triangular extension that provides additional fin area for stabilization during zero speed. Thus, during tests at zero speed the XT foil is present, but during tests in transit the XT foil is not present. The main dimensions of the stabilizer fin are provided below in Table 4 and a detail photograph of the fin on the hull model is shown in below in Figure 5.

<table>
<thead>
<tr>
<th>Stabilizer Fin Dimensions</th>
<th>XT Foil Retracted</th>
<th>XT Foil Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>7.5 m²</td>
<td>9.6 m²</td>
</tr>
<tr>
<td>Balance</td>
<td>20%</td>
<td>-</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>0.36</td>
<td>-</td>
</tr>
</tbody>
</table>

The fins were placed on the hull forward of amidships and as far aft as possible without extending beyond the maximum beam or below the baseline when in the center position. This resulted in a longitudinal position 48.0m forward of the aft perpendicular. A detailed view of the fin placement is provided below in Figure 6; the dimensions are referenced to the pivot point of the fin.

Figure 5 Stabilizer fin on hull model: XT foil fitted
Figure 6 Fin position on hull
4.4 Magnus Rotors

The Magnus rotors fitted to the hull were Quantum’s ML460 rotor units. The primary dimensions of this rotor unit are illustrated below in Figure 7.

![Figure 7 Dimensions of ML460 Magnus rotor](image)

The rotors were placed aft of amidships and as far forward as possible such that the rotor did not protrude below the baseline in its extended position. This resulted in a longitudinal position 32.9m forward of the aft perpendicular. A detailed view of the rotor placement is provided below in Figure 8. The dimensions are referenced to the pivot point of the rotor, which is defined by the intersection of the swing axis and spin axis.

![Figure 8 Rotor position on hull model](image)

![Figure 9 Magnus rotors mounted on the hull](image)

Recessed pockets in the hull house the rotors when they are not in use. When the rotors are stowed in the pockets they are fully within the extents of the hull form, as shown in Figure 9-A. In Figure 9-B, the rotors are shown in their deployed position, perpendicular to the hull. They are fixed in this 90° position during tests in transit, and swing ±60° in a forward-aft direction from this position during tests in zero speed. To “remove” the rotors from the hull for the tests with the XT fins, plugs were fitted into the hull pockets, resulting in a smooth hull surface as shown in Figure 9-C.
4.5 Test Program

The primary objective of the model tests was to compare the performance of the fins and rotors to better understand their individual merits. The test program was developed with the advice of MARIN, and was designed to evaluate the two systems in a variety of sea conditions both in underway and zero speed. In underway, passive and active stabilization tests were carried out at two forward speeds: 7kn and 14kn at multiple combinations of wave conditions (heading, period, and height). In zero speed, a typical seakeeping program was adopted, with passive and active stabilization tests in resonant and off-resonant waves at various wave heights and headings. For the comparison of fins and Magnus rotors the test program was carried out twice: first with fins and then with rotors (although not every condition was repeated due to time limitations). The test program also included several other tests of a more technical and exploratory nature, but as those are outside of the scope of this paper they will not be included in the present analysis.

5. TEST RESULTS

5.1 Zero Speed

The results from the zero speed tests in irregular waves are presented below in Table 5 and Figure 10. The results are presented as roll angles (root mean square) of the non-stabilized and stabilized vessel, as well as the resulting roll reduction percentages.

<table>
<thead>
<tr>
<th>$H_{sig}$ [m]</th>
<th>$T_{modal}$ [s]</th>
<th>Heading [deg]</th>
<th>&quot;Bare Hull&quot;</th>
<th>Fins passive</th>
<th>Fins active</th>
<th>Rotors active</th>
<th>Roll Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>6.5</td>
<td>270 (beam)</td>
<td>1.02*</td>
<td>0.67</td>
<td>0.20</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>2.0</td>
<td>6.5</td>
<td>270 (beam)</td>
<td>2.55*</td>
<td>1.36</td>
<td>0.74</td>
<td></td>
<td>71%</td>
</tr>
<tr>
<td>1.0</td>
<td>10.0</td>
<td>270 (beam)</td>
<td>3.67†</td>
<td>2.90</td>
<td>0.39</td>
<td>0.44</td>
<td>89% 88%</td>
</tr>
<tr>
<td>2.5</td>
<td>10.0</td>
<td>300 (SQ)</td>
<td>9.12†</td>
<td>7.32</td>
<td>5.08</td>
<td>5.40</td>
<td>44% 41%</td>
</tr>
</tbody>
</table>

* Test performed with fins at 90° (trailing edge up)
† Test performed with passive rotors in the deployed position
The results indicate that the tested rotor and fin systems have approximately equal roll reduction capacities in zero speed. In a resonant beam wave of 1.0 m, the fin and rotor systems achieve stabilized RMS roll angles of 0.39° and 0.44° respectively, which represent roll reductions of 89% and 88% as compared to the non-stabilized bare-hull RMS roll angle of 3.67°. The zero speed tests at a significant wave height of 2.5 m were carried out in a stern quartering heading— the “worst-case scenario” according to MARIN’s analysis of the hull form. In this condition, the fins and rotors achieved stabilized RMS roll angles of 5.08° and 5.40° respectively, reduced from 9.12° RMS roll angle measured on the non-stabilized bare-hull. The condition in a 2.5 m wave is not typical in a yachting environment but is important for applications like patrol vessels and offshore applications and is therefore of considerable interest.

A comparison of the non-stabilized roll angles (bare hull vs. passive fins) indicates that the passive fins contribute significantly to the roll damping of the vessel, and this contribution becomes greater for larger roll angles. It should be noted that the “bare-hull” tests were performed either with the fins positioned at 90° (trailing edge up) or the rotors deployed but inactive. The tests were carried out this way to minimize the number of model configurations in order to save time. While the passive appendages do contribute to damping, for the sake of this comparison it is considered to be minimal.

The results from the zero speed tests are also presented in terms of MARIN’s comfort rating in Figure 11. The comfort ratings were analyzed for five different locations aboard the vessel: upper deck, bridge, amidships portside, amidships starboard, and the aft deck. By comparing the comfort ratings achieved by the rotors and fins, it is evident that the results are in agreement with the results suggested by the roll angle analysis: the fins and rotors have approximately equal capacities in zero speed. In comparing the relative change in comfort rating between non-stabilized and stabilized tests, it is apparent that a significant improvement in comfort was achieved particularly in the tests in resonant waves (Tm=10s), whereas in the off-resonance tests (Tm=6.5s), even though the roll angle was reduced through stabilization, only a minor improvement in comfort was achieved. This result points to the fact that the comfort rating depends purely on acceleration, and does not account for the reduction in roll angle beyond the influence that rolling has on accelerations. If other acceleration components are stronger than the roll-induced component, then a reduced roll does not show a marked improvement of the comfort rating.
5.2 Underway
The results from the underway stabilizer tests are presented below in Figure 12 and Table 6.

Figure 11 MARIN comfort rating results for zero speed tests

Figure 12 Results from underway stabilizer tests
Table 6 Results from underway stabilizer tests

<table>
<thead>
<tr>
<th>U [kn]</th>
<th>H\text{sig} [m]</th>
<th>T\text{modal} [s]</th>
<th>Heading [deg]</th>
<th>Non-Stabilized*</th>
<th>Fins active</th>
<th>Rotors active</th>
<th>Roll Reduction [%]</th>
<th>Fins</th>
<th>Rotors</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>2.5</td>
<td>8.0</td>
<td>315</td>
<td>8.33</td>
<td>1.95</td>
<td>1.33</td>
<td>77%</td>
<td>84%</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
<td>8.0</td>
<td>315</td>
<td>10.41</td>
<td>5.20</td>
<td>4.43</td>
<td>50%</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td>2.5</td>
<td>6.5</td>
<td>300</td>
<td>9.36</td>
<td>0.74</td>
<td>1.20</td>
<td>92%</td>
<td>87%</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td>5.0</td>
<td>12.6</td>
<td>135</td>
<td>2.20</td>
<td>0.49</td>
<td>1.46</td>
<td>78%</td>
<td>34%</td>
<td></td>
</tr>
</tbody>
</table>

* Test performed with passive rotors in the deployed position

The results from the 7kn and 14kn tests confirm the predicted outcome that the rotors would outperform the fins below 12kn, and vice versa above 12kn. At 7kn, the comparative stabilizer tests were carried out at two wave heights (2.5m and 5m) in identical wave conditions (period and heading). For these demanding conditions, the non-stabilized RMS roll angles were 8.33° at H\text{sig}=2.5m, and 10.41° at H\text{sig}=5.0m. The rotors produced better stabilized RMS roll angles in both wave heights at 7kn, achieving 1.33° compared to the fin’s 1.95° in the 2.5m condition, and in the 5.0m wave height achieving 4.43° compared to the fin’s 5.20°.

In the underway tests at 14kn the opposite result was observed, as expected, and the fins demonstrated better performance than the rotors. At 14kn, the tests were carried out at two wave heights (2.5m and 5.0m) but at differing wave headings and periods. The 2.5m wave height was a “worst-case scenario” test condition according MARIN’s analysis of the hull form, resulting in a non-stabilized RMS roll angle of 9.4°. The fins and rotors both provided significant stabilization in this condition with stabilized RMS roll angles of 0.74° (92% roll reduction) and 1.2° (87% roll reduction), respectively. The 5.0m test condition was a more favorable heading and wave period, and the non-stabilized vessel experienced a 2.2° RMS roll angle. The fins outperformed the rotors with 0.49° stabilized RMS roll angle as compared to the 1.46° achieved by the rotors.
The results from the underway tests are also presented in terms of MARIN's comfort rating below in Figure 13. Most interesting from this analysis is the marked improvement in comfort particularly in the stern quartering headings. This is likely due to the fact that in stern quartering seas, the frequency of encounter is low and so the acceleration levels are low. However, the sideward gravity acceleration component due to roll angles becomes then significant and so reducing the roll angle has a large influence on the comfort rating.

![Figure 13 MARIN comfort rating results for underway tests](image)

**6. CONCLUSIONS**

The performance of a fin stabilizer system and Magnus-effect rotor stabilizer system was compared in the model tests presented herewith in. From the test results and analysis contained within this report, the following conclusions are drawn:

- As expected the Magnus rotors provided better performance at lower ship speeds
- At higher speeds the fins gave better results
- Magnus rotors can provide a good alternative to fins for ships where: fin placement is problematic; the fold-away capability of rotors is desirable; extra performance at low speeds is desirable.
- The comfort rating provides a useful measure to assess the passenger and crew comfort experience. However, more research is desirable to also include the effects of jerk in a modified or extended comfort rating.

Based on the test results additional tests are already scheduled. One goal is to investigate the jerk which is, at present, not or insufficiently accounted for in comfort ratings but has a significant effect on comfort on-board. Stabilizer systems making abrupt fin motions can induce additional jerk to the extent that people notice and comment on it. However, it is hard to translate this into a quantified amount of discomfort. Although Quantum stabilizers already minimize jerk, being able to measure, quantify, and – if possible – further reduce stabilizer-induced jerk is one goal of the coming tests. Another goal is to test some proposed changes in the control algorithm in order to further improve stabilizer zero speed performance and so further maximize comfort on board.
REFERENCES


