PERFORMANCE EVALUATION AND RANKING OF 7 RUDDERS FOR THE FINN DINGHY

Adam Persson  
SSPA Sweden AB, Sweden, adam.persson@sspa.se

Lars Larsson  
Chalmers University of Technology, Sweden, lars.larsson@chalmers.se

Matz Brown  
SSPA Sweden AB, Sweden, matz.brown@sspa.se

Christian Finnsgård  
Chalmers University of Technology/SSPA Sweden AB, christian.finnsgard@sspa.se

Abstract: As a follow up to the Olympic Games, commercially available Finn dinghy rudders were tested to determine their hydrodynamic performance. Seven rudders were tested, out of the nine different rudder models that were measured for competition at the 2016 Olympic Games, thus representing a large portion of the rudders used by sailors. The remaining two rudder models could not be tested, since they are of semi-custom or custom design or manufacture. Each rudder was tested in seven different conditions, selected to cover a wide range of sailing conditions. The testing revealed considerable differences, both in performance and handling.

Keywords: sailing, Olympic Finn dinghy, rudder, towing tank test, dynamic test, full scale

NOMENCLATURE

$L/D$ Lift to drag ratio [-]  
$F_x$ Drag force [N]  
$F_y$ Side force [N]  
$t_δ$ Rudder oscillation period [s]  
$V$ Carriage speed [ms$^{-1}$]

$δ$ Rudder angle [°]  
$δ_C$ Rudder angle, corrected for initial misalignment [°]  
$μ_w$ Dynamic viscosity, water [Pa s]  
$ρ_w$ Density, water [kgm$^{-3}$]
INTRODUCTION

The Finn Dinghy has a long and prolific history, having been sailed at every summer Olympics since 1952 (Int. Finn Association, 2017). The Finn dinghy is one of two (along with the 470 dinghy) remaining open one-design classes used in the Olympic Games. The Finn class rules (World Sailing, 2015) permit certain design variations of the hull, mast, sail and rudder.

With high and equal levels of sailing skills among Olympic sailors, it is of critical importance to ensure that also the equipment performs at an optimal level. Therefore sailors and national teams spend development money on developing new rudders to gain competitive advantages.

Previous research

A few articles discussing full scale measurements of the forces acting on a sailing boat have been published, concerning sail aerodynamics but also hull hydrodynamic resistance.

Lindstrand et al. (2014) presents a verification and validation study, comparing numerical predictions of hydrodynamic resistance Laser dinghy against full scale towing tank test data.

Finnsgård et al. (2015) give an outlook on potential research directions for improving the performance of Olympic dinghies. As an example, full scale towing tank testing of the Laser dingy (from Lindstrand et al. 2014) is shown. Further applications for full scale towing tank tests are discussed, also for the Finn dinghy.

Liu and Hekkenberg (2017) published a comprehensive review of rudder design and performance for ships, including investigation of the typical operating conditions for a ship rudder, investigation of the influence of section shape as well as the influence of rudder type and planform design. Liu and Hekkenberg suggest that careful characterization of the operating conditions, and that careful replication of these in testing, is critical to a successful evaluation of rudder performance. Scaling effects (Reynolds number), in particular, must be controlled.

While rudder design and performance for ships is explored thoroughly by Liu and Hekkenberg (2017) no such general publications have been found for sailing boats. However, the forces acting on rudders have been measured by several researchers.

In Kuhn and Scragg (1993), measurements and numerical predictions of lift and drag for a surface piercing foil at small angles of attack, ranging from -4° to 8°, are presented. Only static conditions are studied. Kuhn and Scragg showed that, on a surface-piercing lifting foil, two drag contributions could be identified. One due to vorticity that is shed in the wake, and one due to asymmetry of the radiated wave field.

Miller (2007) discusses the measurement of dynamic lift coefficients on spade rudders, using CFD and FEA to determine lift coefficients from strain gauge measurements, but few results are presented. In addition, the drag of the rudders is not measured.

Hochkirch and Brandt (1999) measured forces acting on the hull, rig, keel and rudder in full scale during sailing, using a sailing dynamometer. In addition, model scale tank test results are shown for rudder forces, investigating the influence of three keel designs on rudder forces. However, no variation of the rudder design is tested.

In Larsson et al. (2014), a general discussion on keel and rudder design is presented, based on the well established principles from aircraft aerodynamics, utilizing lifting line theory as well as experimental results. The effects of section and planform shape on lift and drag are discussed, with some applicability to Finn dinghy rudder design.
To conclude, while rudder design for ships has been studied, no studies investigating rudder design for the dinghies has been found. The Finn dinghy rudder is different from ship rudders. Firstly, it is surface piercing. Secondly, the operating conditions for a dinghy rudder is much more dynamic. In addition, the Finn class rules pose restrictions on design, reducing the relevance of more general previous studies.

Purpose

The purpose of this paper is to identify variations in performance, and handling characteristics, for seven commercially available Finn dinghy rudders. To identify variations in performance, an experimental evaluation method was developed, providing a basis for further testing. The experimental setup, methodology and selected cases will also be presented and discussed.

THE FINN DINGHY RUDDER

The Finn dinghy uses a transom hung rudder, with a swept elliptical planform. The design is controlled by the class rules (World Sailing, 2015) which allow variation of the design within certain limits.

A measurement point, called point 'K' is defined by the rules. This point corresponds to the intersection between the rudder leading edge and the measurement waterline. Above point 'K', the planform shape is free. Below point 'K', the planform shape of the rudder must be within ±5 mm of the prescribed planform shape. The limits as defined in the class rules are shown approximately in Figure 1.

In addition to the planform limitations, some limitations are also imposed on the thickness and chord length of the rudder section. Below point 'K', the thickness may not exceed 23 mm, while the chord length may not exceed 365 mm. Compliance with these limitations is checked by passing a template over the rudder blade.

The longitudinal position of the rudder axis relative to the boat is also specified, where the distance from the transom to the rudder axis must be between 10–30 mm. The rudder axis inclination may also vary by 0.5 degrees.

Figure 1. Approximate Finn dinghy rudder outline and rule planform limits (Interpreted from World Sailing, 2015)
Modification to the planform and rudder axis inclination could be used to alter the span wise load distribution, reducing induced resistance or reducing wave making resistance and risk of ventilation. Larsson et al. (2014) discuss the effect of sweep angle, concluding that for an elliptic planform, the optimal sweep angle is 0 degrees.

The planform of the Finn rudder is close to elliptic, and should thus have a low sweep angle. This can be changed in two ways whilst staying within the class rules; modification of the planform to reduce the sweep angle, or changing the rudder axis inclination to reduce the sweep for the entire blade. These modification could, according to Larsson et al. (2014), reduce the induced resistance by bringing the span wise lift distribution closer to elliptical.

In addition, it may be possible to utilize advanced planform design concepts within the confines of the rule, such as tubercles, which may lead to improved performance in certain conditions.

While the maximum chord length and thickness is controlled by the rule, there is still significant room for variation of the profile shape. This allows tailoring the rudder characteristics to the intended operating conditions, for example by choosing a low drag, low maximum lift airfoil section for a light air rudder, or choosing an airfoil section with higher drag, but also higher maximum lift, for a heavy air rudder. The section shape could also be varied span-wise.

**SELECTION OF TEST CASES**

Seven rudders were tested, out of the nine different rudder models that were measured for competition at the 2016 Olympic Games, thus representing a large portion of the rudders used by sailors. The remaining two rudder models could not be tested, since they are of semi-custom or custom design or manufacture. The results presented are anonymized.

Each rudder was tested in 7 different conditions, selected to represent sailing conditions ranging from light downwind, sailing upwind in waves with heavy rudder motion and also including high angle of attack/rudder loading as may be seen when bearing away in heavy winds. This ensures that the evaluated performance is relevant to the sailing performance.

**Static cases**

Two static test cases were chosen, $\delta = 0^\circ$ and $\delta = 5^\circ$. The $\delta = 0^\circ$ case was chosen to allow measurement of the parasitic and wave drag contributions at zero rudder angle, which is of importance for light air sailing. The $\delta = 5^\circ$ case represents sailing upwind or reaching in smooth water, where a small constant rudder angle is needed to generate side force and ensure balance (yaw equilibrium). These angles were chosen based on discussion with elite Finn sailors. However, the test matrix was expanded to cover intermediate angles, higher rudder angles as well as negative rudder angles, allowing interpolation of the results.

The rudder angles have not been corrected for leeway, which will slightly increase the rudder effective angle of attack. Because of the downwash from the centerboard, the effective angle of attack on the rudder is equal to the rudder angle plus half the leeway angle.

**Dynamic cases**

Two dynamic cases were tested, with the rudder angle varying with a sinusoidal wave function. The first case, representing upwind sailing in waves, had a rudder angle amplitude of $\delta = \pm 15^\circ$ and an oscillation period of $t_\delta = 1.5$ s. The amplitude and oscillation period were determined from mast camera footage of a Finn dinghy sailing upwind in moderate wave conditions. A frame capture from the mast camera footage can be seen in Figure 2.
The second dynamic case was chosen to determine the characteristics of the rudders at high angles of attack, which can occur during a heavy-air bear-away, where significant rudder force may be required to overcome the yawing moment generated by the sail plan. The resulting high load on the rudder, may cause ventilation to occur on surface piercing rudders, which could lead to loss of control. In order to stimulate ventilation, a test case with a slow oscillation was used, with rudder angle amplitude of $\delta = \pm 20^\circ$ and an oscillation period of $t_\delta = 12.58$ s.

**EXPERIMENTAL SETUP**

In this section, the experimental procedures used to evaluate the rudders hydrodynamic performance will be reviewed, limitations motivated, and implications explained.

**Hull model construction**

As was concluded by Liu and Hekkenberg (2017), careful replication of realistic operating conditions is necessary for successful evaluation of rudder performance. Considering this, the test was run in full scale. In addition, a hull dummy was included, so that the influence of hull wake and transom waves can be included. The hull wake and transom waves will modify the inflow to the rudder, introducing a vertical velocity component to the flow, and greatly affect the wave making around the rudder head.

Due to the need to fit an oscillation mechanism and a force dynamometer, a real Finn dinghy hull could not be used for the towing tank tests. Instead, a modern Finn dinghy hull (2015 model, Devoti manufactured, “Fantastica”-form) was 3D-scanned to produce an accurate CAD description of the hull. A full-scale hull dummy was then manufactured from polyurethane foam, using CNC-machining.

The deck surfaces were adapted so as to provide the necessary space and mounting points for the measurement equipment. The hull sides were extended vertically to provide a horizontal deck line, aiding manufacturing and mounting. The transom was recessed, ensuring clearance between the measurement equipment and the hull dummy, so that no forces are transmitted between the two inadvertently.
Rudder oscillation mechanism and force measurement instrumentation

To allow dynamic tests with an oscillating rudder angle, the rudder angle is controlled by a servo actuator, driven by a computer program. In this way, the rudder angle amplitude could easily be adjusted between $0 - 20^\circ$. The rudder oscillation period could also be adjusted, albeit with some limitations due to the control software. The use of a servo actuator also allowed efficient variation of angle of attack for static measurements. A rotary encoder is used to measure the achieved rudder angle, accurate to $\pm 0.1^\circ$.

The complete rudder oscillation mechanism, with rudder brackets, is then mounted to the dynamometer. This ensures that the forces are measured in the correct direction. The dynamometer is rigidly mounted to the towing carriage. An overview of the arrangement is shown in Figure 4.

The dynamometer used was a six-component strain gauge balance, measuring force components in X, Y, Z-direction as well as moments around these axes. The dynamometer was calibrated for a measurement range of maximum 500 N.

All signals, forces, moments as well as rudder angle and carriage speed were sampled at 100 Hz. No forces were measured on the hull dummy.
Hull and rudder positioning

The hull dummy was rigidly attached to the towing carriage, fixed in all degrees of freedom (in relation to the towing carriage). The draft of the hull corresponded to a displacement of 240 kg. The displacement was derived from a fully equipped sailing dinghy, sailor and equipment. The trim was then adjusted so the transom edge touches the still water surface.

The lower rudder gudgeon was positioned at a height of 50 mm above the water line. All of the tested rudders were supplied with the required hardware pre-mounted at standard positions. This resulted in a distance from transom to rudder axis of 16 mm. A second positioning, with a 14 mm spacer between the transom and rudder bracket, bringing the distance between transom and rudder axis to total of 30 mm. No modifications to the mounting hardware were made.

The rigid mounting of the hull and rudder mechanism to the towing carriage constitutes an important simplification, since a sailing Finn dinghy would react to the side force created by the rudder deflection, leading to a yawing motion. Such a motion would reduce the effective angle of attack of the rudder, reducing the maximum side force generated by the rudder.

However, such a simplification was deemed necessary for practical experimental reasons. The dynamometer and mechanical equipment associated with the rudder oscillation are heavy, weighing significantly more than the 240 kg displacement expected for a sailing Finn dinghy, meaning that it would not be possible to support the arrangement on a floating Finn dinghy hull. Thus, the hull would have to be constrained in sinkage, allowing the additional weight to be transferred to the towing carriage, whilst allowing free yawing motion.
In addition, even if such an arrangement could be constructed, the large additional mass of the dynamometer and rudder oscillation mechanism, which is positioned at the stern, would affect the rotational inertia, and thus, the yawing response of the boat.

Considering the implications discussed above, rigidly fixing the boat to the towing carriage was considered an acceptable simplification, greatly reducing the complexity of the experimental setup, whilst still providing relevant results.

Since the purpose of the test was to compare different rudder designs, neglecting leeway and the small effect this has on the effective angle of attack on the rudder, was considered acceptable. A small change in the angle of attack should not affect the ranking of the rudders, given the large range of tested rudder angles.

Also, with the boat fixed, any roll angles that may be present during sailing are neglected. Considering that the Finn dinghy is sailed as upright as possible, this effect is considered negligible.

**Environmental conditions**

The towing tank tests were conducted at SSPA Sweden AB in Gothenburg. The dimensions of the towing tank used were $260 \times 10 \times 5$ m. The carriage has a maximum velocity of 11 m/s, with velocity controlled to 0.001 m/s. The carriage speed for all tests was $V = 2.315$ m/s.

The water temperature was 16.9°C for all tests performed. According to the ITTC Recommended Procedures, this corresponds to the physical properties shown in Table 1.

<table>
<thead>
<tr>
<th>$t$ (°C)</th>
<th>$\rho$ (kgm$^{-3}$)</th>
<th>$\mu$ (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.9</td>
<td>998.7953</td>
<td>0.001083</td>
</tr>
</tbody>
</table>

Since the model is towed through still water, the background turbulence intensity can be assumed to be very low. However, after several consecutive runs, the background turbulence will be increased, due to turbulence created by the lift generating rudder and surface waves created by the hull and rudder. To evaluate the influence of this, several tests were repeated, showing repeatability within 0.5% for both side force and drag.

**Post processing**

The static results presented below are averages of the measured time series. The force measurement was started after the acceleration period and stopped before deceleration, ensuring that only steady forces were included. On average, the time series are 52 s long.

Despite careful positioning of the rudders, some initial rudder angle misalignment is present, which also varies between the rudders tested. This has the potential to greatly affect the results at low angles of attack, where the misalignment is large in relation to the rudder angle to be tested.

In order to correct for this, the misalignment was estimated, using a first degree polynomial to determine the zero side force intercept. The rudder angles were then corrected using this value. In order to provide comparisons at the same rudder angle, the interpolated values are used for performance evaluation. In addition, the raw experimental data is also presented.

The dynamic results required more significant post-processing. Since the dynamometer is rigidly mounted to the towing carriage, vibrations from the carriage are easily transmitted, which can clearly be seen in the measurements. Play and backlash in the oscillation mechanism as well as the dynamometer also results in noise in the force measurements.
Because of the above-mentioned noise, the dynamic time series were filtered in the frequency domain. A Fast Fourier Transform (FFT) was used to transfer the results to the frequency domain. The resulting spectrum was then filtered to isolate the frequencies of interest. In Figure 5, a representative comparison of filtered and unfiltered signals is shown.

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Figure 5. Comparison of unfiltered and filtered signals

**STATIC RESULTS**

Table 2 shows the zero-lift drag as interpolated from the rudder angle sweeps, showing a maximum difference of 15%. However, it should be noted that the absolute differences in comparison to the measurement range of the dynamometer is very small.

<table>
<thead>
<tr>
<th>Rudder</th>
<th>1</th>
<th>1 (spacer)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx</td>
<td>-1.81</td>
<td>-1.97</td>
<td>-1.98</td>
<td>-2.07</td>
<td>-1.90</td>
<td>-1.87</td>
<td>-1.89</td>
<td>-2.13</td>
</tr>
</tbody>
</table>

Table 3 gives the estimated initial misalignment, determined using a first degree polynomial fit to find the rudder angle corresponding to zero side force.

<table>
<thead>
<tr>
<th>Rudder</th>
<th>1</th>
<th>1 (spacer)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δδ (°)</td>
<td>-0.22</td>
<td>-0.29</td>
<td>0.03</td>
<td>0.28</td>
<td>-0.41</td>
<td>-0.14</td>
<td>-0.43</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

Table 4 shows raw, measured data (drag and side force) for the different rudders at actual rudder angles (δ) between 1-10°.
Table 4. Drag and side force for actual rudder angles $\delta \approx 1 - 10^\circ$

<table>
<thead>
<tr>
<th>Rudder</th>
<th>$\delta$</th>
<th>$F_x$</th>
<th>$F_y$</th>
<th>$\delta$</th>
<th>$F_x$</th>
<th>$F_y$</th>
<th>$\delta$</th>
<th>$F_x$</th>
<th>$F_y$</th>
<th>$\delta$</th>
<th>$F_x$</th>
<th>$F_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78</td>
<td>-1.92</td>
<td>14.78</td>
<td>-2.34</td>
<td>30.1</td>
<td>-5.87</td>
<td>90.9</td>
<td>9.78</td>
<td>-18.6</td>
<td>193</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (spacer)</td>
<td>0.71</td>
<td>-2.1</td>
<td>13.3</td>
<td>1.71</td>
<td>-2.53</td>
<td>32.1</td>
<td>-6.63</td>
<td>99.6</td>
<td>9.71</td>
<td>-21.6</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
<td>-2.08</td>
<td>15.5</td>
<td>2.03</td>
<td>-2.44</td>
<td>33.8</td>
<td>-5.59</td>
<td>88.4</td>
<td>10.03</td>
<td>-18.3</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.28</td>
<td>-2.35</td>
<td>23.28</td>
<td>-2.95</td>
<td>41.9</td>
<td>5.28</td>
<td>-7.28</td>
<td>102.0</td>
<td>10.28</td>
<td>-22.9</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.59</td>
<td>-2.02</td>
<td>7.7</td>
<td>1.59</td>
<td>-2.25</td>
<td>25.9</td>
<td>4.59</td>
<td>-5.28</td>
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<td>9.59</td>
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<td>168</td>
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<tr>
<td>5</td>
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<td>-2.03</td>
<td>13.5</td>
<td>1.86</td>
<td>-2.5</td>
<td>32.6</td>
<td>4.86</td>
<td>-6.31</td>
<td>90.6</td>
<td>9.86</td>
<td>-18.9</td>
<td>195</td>
</tr>
<tr>
<td>6</td>
<td>0.58</td>
<td>-1.97</td>
<td>8.58</td>
<td>-2.26</td>
<td>27.4</td>
<td>4.58</td>
<td>-5.4</td>
<td>83.5</td>
<td>9.58</td>
<td>-19.8</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.71</td>
<td>-2.27</td>
<td>14.8</td>
<td>1.71</td>
<td>-2.7</td>
<td>31.1</td>
<td>4.71</td>
<td>-6.05</td>
<td>90.8</td>
<td>9.71</td>
<td>-18.1</td>
<td>189</td>
</tr>
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</table>

Table 5 shows the interpolated drag and side force for the different rudders, at corrected rudder angles, $\delta_c = 1 - 10^\circ$. Since the values are corrected for initial misalignment, they allow fair comparison of the performance of the rudders.

Table 5. Drag and side force for corrected rudder angles $\delta_c = 1 - 10^\circ$

<table>
<thead>
<tr>
<th>$\delta_c$</th>
<th>1°</th>
<th>2°</th>
<th>5°</th>
<th>10°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudder</td>
<td>$F_x$</td>
<td>$F_y$</td>
<td>$F_x$</td>
<td>$F_y$</td>
</tr>
<tr>
<td>1</td>
<td>-2.17</td>
<td>19.4</td>
<td>-2.49</td>
<td>36.8</td>
</tr>
<tr>
<td>1 (spacer)</td>
<td>-1.94</td>
<td>18.3</td>
<td>-2.43</td>
<td>36.3</td>
</tr>
<tr>
<td>2</td>
<td>-2.15</td>
<td>19.7</td>
<td>-2.73</td>
<td>39.3</td>
</tr>
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<td>3</td>
<td>-2.14</td>
<td>17.3</td>
<td>-2.54</td>
<td>34.6</td>
</tr>
<tr>
<td>4</td>
<td>-2.15</td>
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<td>5</td>
<td>-1.90</td>
<td>19.1</td>
<td>-2.50</td>
<td>38.1</td>
</tr>
<tr>
<td>6</td>
<td>-2.36</td>
<td>19.4</td>
<td>-2.84</td>
<td>38.7</td>
</tr>
</tbody>
</table>

Table 6 shows the lift drag ratio for corrected rudder angles, $\delta_c = 1 - 10^\circ$. At 1° rudder angle, rudder 1 with spacer gives the highest $L/D$ ratio at 10.1, while rudder 1 without spacer gives the second highest $L/D$ ratio, which is 1.8% higher than the third best (nr. 6) and 15.7% higher than the worst rudder (nr. 4).

At 2° rudder angle, rudder 6 now gives the highest $L/D$ ratio, with a small advantage (1.2%) over rudder 1. At this rudder angle, the spacer has no effect on the $L/D$ ratio of rudder 1. Rudder 2 has the third highest $L/D$, at 5° below rudder 6. Rudder 4 gives the lowest $L/D$, at 14.6% lower than rudder 6.

At 5° rudder angle, rudder 2 gives the highest $L/D$. Rudder 1 gives 5% lower $L/D$ compared to rudder 2. Rudder 6 now gives the third highest $L/D$, 5.5% lower than rudder 2. Rudder 3 now gives the lowest $L/D$, at 10.4% lower than rudder 2.

At 10° rudder angle, rudder 4 now gives the highest $L/D$. Rudder 7 gives second highest $L/D$, which is 2.9% lower. Rudder 1 is third best, with a 4.8% lower $L/D$. The worst rudder is now rudder 6, with 15.9% lower $L/D$ compared to rudder 4.
Table 6. Lift/drag ratio for corrected rudder angles $\delta_C = 1 - 10^\circ$

<table>
<thead>
<tr>
<th>Rudder</th>
<th>$F_y/F_x$</th>
<th>$F_y/F_x$</th>
<th>$F_y/F_x$</th>
<th>$F_y/F_x$</th>
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<tbody>
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<td>1</td>
<td>9.85</td>
<td>15.5</td>
<td>15.5</td>
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<td>1 (spacer)</td>
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<td>15.5</td>
<td>14.8</td>
<td>9.44</td>
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<tr>
<td>2</td>
<td>8.87</td>
<td>14.9</td>
<td>16.3</td>
<td>9.93</td>
</tr>
<tr>
<td>3</td>
<td>8.89</td>
<td>14.3</td>
<td>14.6</td>
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<tr>
<td>4</td>
<td>8.30</td>
<td>13.4</td>
<td>14.8</td>
<td>10.5</td>
</tr>
<tr>
<td>5</td>
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<td>14.7</td>
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<td>6</td>
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<td>15.7</td>
<td>15.4</td>
<td>8.83</td>
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<tr>
<td>7</td>
<td>8.36</td>
<td>13.5</td>
<td>14.8</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Figure 6 shows resistance plotted against the square of side force, giving an approximately linear relationship. To aid comparison, a linear fit has been plotted. The gradient of the linear fit shows the rate of increase of drag as side force increases. A smaller gradient indicates a more efficient rudder.

Rudders 1, 1 with spacer, 5 and 7 are tightly grouped, with a lower gradient than for the others. Comparing rudder 1 with and without spacer, the spacer has a lower gradient, indicating a more efficient rudder.

Figure 6. Variation of drag with side force squared
Figure 7 shows resistance and side force plotted against rudder angle. A 3rd degree curve has been fitted to the drag data, whilst a linear fit is shown for side force. Considering the generated side force, 4 out of 7 rudders are tightly grouped, with similar side force gradients. Rudders 2 and 4 show a lower side force gradient, but also generate lower drag. The addition of a spacer has a significant effect on rudder 1, greatly increasing the side force gradient, but also increasing the drag.

Figure 7. Variation of drag and side force with rudder angle
Figure 8 shows a comparison of the free surface behavior of rudder 4 and rudder 6 at $\delta = 1^\circ - 10^\circ$. While a large part of the difference shown above may be attributed to different planform and section design, Figure 8 demonstrates that the design of the rudder head and brackets can significantly influence the rudder performance.

Figure 8(a) shows the clean inflow observed on rudder 4, where the water climbs up the leading edge and is then cleanly broken away by the rudder head and bracket. Figure 8(b) shows rudder 6, where a disturbed inflow was observed, creating a spilling wave rolling down towards the leading edge.

Of the tested rudders, rudders 3 and 4 have very similar, low disturbance, free surface behavior. The other rudders have a spilling wave surrounding the leading edge.

![Figure 8](image1.png)

Figure 8. Comparison of two rudders at $10^\circ$ rudder angle. Note difference at leading edge.

Figure 9 shows a comparison of rudder 1, with and without spacer. The spacer increases the distance between the transom and the rudder axis, changing the position of the rudder relative to the transom wave system generated by the boat. With increased distance, the transom wave can climb further up the rudder blade, increasing the effective rudder area, and thus, explaining the increase in both side force and drag that can be seen.

![Figure 9](image2.png)

Figure 9. Comparison of rudder 1, with or without spacer, at $10^\circ$ rudder angle.
DYNAMIC RESULTS

Table 7 shows mean and peak values for drag and side force for the dynamic test with $\delta = \pm 15^\circ$. Rudder 4 gives the least drag, but consistently generates less side force than the other rudders, with 18.4% less drag but also 14.2% lower side force compared to rudder 3, which generated maximum side force (neglecting rudder 1 with spacer). Thus, the side force/drag ratio of rudders 3, 4, 5 and 7 are very similar. Rudders 1, 2 and 6 show worse performance, but rudder 1 (spacer) is worst, with an $L/D$ ratio 28% lower than rudder 5.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>1 (spacer)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$</td>
<td>-24.4</td>
<td>-30.5</td>
<td>-25</td>
<td>-22.8</td>
<td>-18.6</td>
<td>-21.7</td>
<td>-24.4</td>
<td>-21</td>
</tr>
<tr>
<td>$\bar{F}_x$</td>
<td>-55.2</td>
<td>-71.6</td>
<td>-65.1</td>
<td>-48.1</td>
<td>-41.3</td>
<td>-45.9</td>
<td>-55.2</td>
<td>-43.7</td>
</tr>
<tr>
<td>$F_y$</td>
<td>310</td>
<td>355</td>
<td>303</td>
<td>322</td>
<td>276</td>
<td>321</td>
<td>310</td>
<td>301</td>
</tr>
<tr>
<td>$\bar{F}_y / F_x$</td>
<td>5.6</td>
<td>5.0</td>
<td>4.7</td>
<td>6.7</td>
<td>6.7</td>
<td>7</td>
<td>5.6</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Figure 10 shows the time series of rudder angle, drag and side force for the 7 different rudders. Rudders 2 and 7 demonstrate significantly asymmetrical drag curves, with higher drag at negative rudder angles. However, no significant asymmetry is seen in the side force curve, thus ruling out misalignment as the cause. Instead, the asymmetry can most likely be attributed to the rudder head or mounting hardware, for example where screws are countersunk on one side, but left exposed on the other side.
Table 8 shows mean and peak values for drag and side force for the dynamic test with \( \delta = \pm 20^\circ \). Again, gives the lowest drag along, but now also gives the highest \( L/D \) ratio. Rudder 1 with spacer along with rudder 7 shows a considerably lower ratio.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>1 (spacer)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_X )</td>
<td>-55.8</td>
<td>-69</td>
<td>-46.5</td>
<td>-50.9</td>
<td>-40.6</td>
<td>-49.9</td>
<td>-51.8</td>
<td>-49</td>
</tr>
<tr>
<td>( F_Y )</td>
<td>-125</td>
<td>-152</td>
<td>-100</td>
<td>-109</td>
<td>-90</td>
<td>-109</td>
<td>-110</td>
<td>-107</td>
</tr>
<tr>
<td>( F_Y/F_X )</td>
<td>428</td>
<td>344</td>
<td>376</td>
<td>391</td>
<td>381</td>
<td>430</td>
<td>413</td>
<td>309</td>
</tr>
</tbody>
</table>

Figure 11 shows the time series of rudder angle, drag and side force for the 7 different rudders, for the dynamic test with \( \delta = \pm 20^\circ \). This case was tested in an effort to identify differences in ventilation behavior. However, this cannot be seen in the force time series.

Figure 11. Variation of drag and side force with rudder angle
The sensitivity to ventilation inception was instead estimated by counting the frequency of ventilation, as identified visually from the video captured during the towing tank test. A comparison of frame captures for rudders 2 and 4 is shown in Figure 11. A ventilation bubble is clearly visible in Figure 11a.

![Figure 11. Comparison of ventilation behavior for rudders 2 and 4.](image)

**Figure 11. Comparison of ventilation behavior for rudders 2 and 4.** A ventilation bubble is clearly visible in Figure 11a.

The number of ventilation events observed during a towing tank run is presented in Table 7. Each rudder was observed for 4 periods (equal to 8 maximum rudder deflections). The ventilation frequency is reported as the percentage of maximum rudder deflections that showed ventilation.

<table>
<thead>
<tr>
<th>Rudder</th>
<th>1</th>
<th>1 (spacer)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation freq. (%)</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>75</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Large differences in the observed ventilation behavior can be seen, with some rudders completely insensitive to ventilation at 20° rudder angle, and other rudders ventilating 100% of the time. There appears to be no clear correlation between the other tested characteristics and ventilation sensitivity. However, the distance between transom and rudder leading edge seems to have a significant influence on the ventilation sensitivity. Rudder 1, in the original position, showed a 50% ventilation frequency, while rudder 1 with spacers showed a 100% ventilation frequency.

**DISCUSSION AND CONCLUSIONS**

Full scale towing tank testing was used to determine the performance of 7 commercially available Finn dinghy rudders. The test cases were selected to represent realistic sailing scenarios, thus allowing the actual sailing performance to be estimated. The practical contributions in the paper consists of the performance evaluation of the rudders and the ranking of their performance. The theoretical contributions include the development of a testing methodology for testing rudders for sailing dinghies, an area scarcely reported in previous literature.

Significant differences in the generated side force and associated drag was found, with up to 21% less drag found, albeit with a lower side force. By utilizing the rule tolerances,
planform shape could be optimized to reduce the induced resistance, whilst section shape could be optimized to reduce profile drag and wave resistance.

Differences were also found concerning the free surface behavior around the rudders. An improved design would allow the wave resistance to be reduced. If the spray can be broken off earlier, a wetted surface reduction could be achieved, lowering frictional resistance. Also, it may be possible to achieve a more benign ventilation behavior at high angles of attack, thus improving the handling characteristics of the rudder.

Concerning the issue of ventilation; this is frequently pointed out by sailors as a distinguishing feature between different rudders. Thus, it is surprising that no effect can be seen on the force measurements, as a clear reduction in side force is expected when the rudder is ventilated. One explanation for this may be that only partial ventilation was found in the tests, and that with further rudder deflection, the ventilation would increase, limiting the side force. Unfortunately, due to limitations in experimental time, there was no opportunity to investigate this matter further.

Based on the measured lift drag ratio for the different test cases as well as sensitivity to ventilation the rudders were ranked, as is shown in Table 10. Each rudder was given a sub-score of 1-8. If two or more rudders showed similar performance, they were awarded the same score. The sub-scores were then added up with an equal weighting, and the rudder with the lowest total score was ranked as 1st, the next lowest total score ranked 2nd, and so on. If two rudders have the same total score, static $L/D$ ratio is used as a tie breaker. Using the procedure above, rudder 5 was ranked as having the best overall performance.

<table>
<thead>
<tr>
<th>Table 10. Overall rudder ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudder</td>
</tr>
<tr>
<td>$\delta = 1 - 10^\circ$</td>
</tr>
<tr>
<td>$\delta = \pm 15^\circ$</td>
</tr>
<tr>
<td>$\delta = \pm 20^\circ$</td>
</tr>
<tr>
<td>Ventilation</td>
</tr>
<tr>
<td>Overall ranking</td>
</tr>
</tbody>
</table>

The equal weighting of all sub scores, as done above, may be questioned. However, if the goal is to evaluate all-round performance of a rudder, this is deemed to be the most suitable approach. A rule change has recently been accepted, allowing only one rudder to be used at championships. Thus, the importance of all-round performance is emphasized.

However, if a rudder was to be used at a certain venue or under certain conditions, the weighting might have to be adapted. If a rudder is to be used in light wind, low sea state conditions, performance at high angles of attack and ventilation resistance might be sacrificed for a gain in static, low angle $L/D$ ratio.

The opposite is true for heavy wind, high sea state conditions, where high ventilation sensitivity might lead to a boat which is very hard to maneuver.

Concluding these results, it is clear that there is potential for significant drag reductions at typical sailing rudder angles, whilst simultaneously improving handling characteristics and behavior at high rudder angles.

Careful design of the rudder head and brackets is required to avoid additional parasitic drag. CFD, towing tank tests as well as sea trials should be used to ensure optimum performance.
and handling. The development of the Olympic Finn Class rudder is by no means done, and further performance exploits are yet to come.

Acknowledgements

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REFERENCES


