Rating-Based Maneuverability Standards

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ABSTRACT

This paper describes the background of the development of a rating-based maneuvering standard which combines the IMO requirements as a minimum with a slightly improved rating-based system. The rating-based system was developed for the US Coast Guard in the early 80’s. It is based on a large amount of full-scale (builder’s) trials data.

The described combination of the rating system with IMO standards allows a numerical evaluation of how a vessel exceeds minimum requirements. This paper then provides a sample application of this standard to a hypothetical vessel which scores well. The paper also contains a review of future directions in the development of improved maneuvering standards.

INTRODUCTION

In 2002 the International Maritime Organization (IMO) adopted standards for ship maneuverability (IMO 2002a and b). The IMO standards now have recommendatory status until they are mandated and enforced by the governments of the IMO member states.

The IMO standards evolved over a long period of time before they were formulated into the present form. A comprehensive review of this evolution is available in Daidola, et al (2002).

The IMO standards are applicable to vessels with length over 100 m and gas/chemical carriers, regardless of length but do not apply to high speed craft. All types of rudders and propulsion devices are covered by these standards.

These standards are based on the assumption that the maneuverability of a vessel can be judged by comparing some characteristics of trajectories of standard maneuvers. The following four maneuvering capabilities are included in the mandatory standards:

• Turning ability; measured by tactical diameter and advance of the turning circle maneuver;
• Course changing and yaw checking ability, measured by the first and the second overshoot angles of the zig-zag maneuvers.
• Initial turning ability, measured by distance traveled before a vessel changes course 10 degrees during a zig-zag maneuver;
• Stopping ability, measured by the track reach from a crash stop test.

In addition, straight line stability / course-keeping ability is also included in the standards. The measure is the width of the instability loop obtained from a spiral maneuver.

According to the IMO standards, these maneuvers are to be performed during sea trials with the vessel in full load condition.

Performing sea trials in the full load condition is not often practical, however. Alternatively, the IMO standards allow carrying out maneuvering assessment based on prediction; however the method of prediction has to be validated with the full-scale trials. If the sea trials are to validate the predictions only, the requirement for full load conditions is not applied and the sea trials can be performed at any loading provided there is sufficient immersion of the propeller and rudder.

By their very nature the IMO standards are minimal standards. They define the minimal level of maneuvering performance representing an internationally accepted level of safety. The relationship between maneuverability and safety is considered by Biancardi et al (1994) with the following benefits to ship owners from incorporating maneuverability and safety highlighted:

- improved operational performance
- reduced cost of training
- reduced down-time for repairs
- reduced losses due to failure to deliver on time

In the early 1980's SNAME T&R panel was working on review.

The US Coast Guard funded research aimed at developing performance-based maneuvering standards. The outcome of this research (Barr et al, 1981) was a rating system of maneuvering criteria, which not only established a minimally acceptable standard, but also gave credit for enhanced maneuvering performance.

This paper describes an effort to make this rating system consistent with the IMO maneuvering standards in a way that the minimal rating would exactly correspond to IMO standards. The rating then would show qualitatively and quantitatively how much this particular design was better than the minimally accepted IMO level. This approach is implemented in the recently published ABS Guide for Vessel Maneuverability (ABS 2006).

### OVERVIEW OF CRITERIA

An overview comparing the criteria resulting from this effort with IMO and Barr et al (1981) is given in Table 1. As can be seen from the table, tactical diameter, the first overshoot angles in 10/10 and 20/20 zig-zag tests and distance traveled before 10 degrees course change in the 10/10 zig-zag test are present in both the IMO requirements and the rating system by Barr et al (1981). The concept and application of a rating procedure based on an overall maneuverability index that synthesizes individual assessments of maneuvering characteristics is discussed in detail by Spyrou (1994).

<table>
<thead>
<tr>
<th>Measure of maneuverability</th>
<th>Criteria and standard</th>
<th>Maneuver</th>
<th>IMO Requirement and Status</th>
<th>Rating System by (Barr et al 1981)</th>
<th>ABS Guide Requirement and Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning Ability</td>
<td>Tactical Diameter</td>
<td>Turning Circle</td>
<td>Mandatory, $TD&lt;5L$</td>
<td>Rating: Marginal to Superior</td>
<td>Mandatory, rated $Rtd≥1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advance</td>
<td>Mandatory, $AD&lt;4.5L$</td>
<td>No criteria</td>
<td>Mandatory, not rated $AD&lt;4.5L$</td>
</tr>
<tr>
<td>Course Changing and Yaw Checking Ability</td>
<td>First Overshoot Angle</td>
<td>10/10 Zig-zag test</td>
<td>Mandatory $\alpha_{101}≤f_{101}(L/V)$</td>
<td>Rating: Marginal to Superior</td>
<td>Mandatory, rated $Rt\alpha_{10}≥1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Overshoot Angle</td>
<td>Mandatory $\alpha_{102}≤f_{102}(L/V)$</td>
<td>No criteria</td>
<td>Mandatory, not rated $\alpha_{102}≤f_{102}(L/V)$</td>
</tr>
<tr>
<td>Initial Turning Ability</td>
<td>Distance traveled before 10 degrees course change</td>
<td>10/10 Zig-zag test</td>
<td>Mandatory $l_{10}≤2.5L$</td>
<td>Rating: Marginal to Superior</td>
<td>Mandatory, rated $Rti≥1$</td>
</tr>
<tr>
<td>Stopping Ability</td>
<td>Track Reach</td>
<td>Crash stop</td>
<td>Mandatory $TR&lt;15L$</td>
<td>No criteria</td>
<td>Mandatory $TR&lt;15L$</td>
</tr>
<tr>
<td></td>
<td>Head Reach</td>
<td>None</td>
<td>Rating: Marginal to Superior</td>
<td>Mandatory Rated $Rt≤1$</td>
<td></td>
</tr>
<tr>
<td>Straight Line Stability and Course Keeping Ability</td>
<td>Residual turning rate</td>
<td>Pull-out test</td>
<td>Recommended $r≠0$</td>
<td>No criteria</td>
<td>Recommended $r≠0$</td>
</tr>
<tr>
<td></td>
<td>Width of instability$^2$ loop</td>
<td>Simplified spiral</td>
<td>Recommended $\alpha_{10}≤f_{10}(L/V)$</td>
<td>No criteria</td>
<td>Not rated $\alpha_{10}≤f_{10}(L/V)$</td>
</tr>
</tbody>
</table>

$^1$ For large, low-powered vessels $TR<20L$

$^2$ Applicable only for path-unstable vessels
The following symbols are used in Table 1:

- \( L \) \text{ length of the vessel, in m, measured between perpendiculars}
- \( TD \) \text{ tactical diameter, in m}
- \( AD \) \text{ advance, in m}
- \( HR \) \text{ head reach, in m}
- \( TR \) \text{ track reach, in m}
- \( \alpha_U \) \text{ width of instability loop, in degrees}
- \( \alpha_{101} \) \text{ the first overshoot angle in the 10/10 zigzag test, in degrees}
- \( \alpha_{102} \) \text{ the second overshoot angle in the 10/10 zigzag test, in degrees}
- \( \alpha_{201} \) \text{ the first overshoot angle in the 20/20 zigzag test, in degrees}
- \( f_{101}(L/V) \) \text{ criterion for the first overshoot angle in the 10/10 zigzag test, in degrees}
- \( f_{102}(L/V) \) \text{ criterion for the second overshoot angle in the 10/10 zigzag test, in degrees}
- \( f_D(L/V) \) \text{ criterion for the width of instability loop, in degrees}
- \( l_{10} \) \text{ distance traveled before 10 degrees course change, in m}
- \( V \) \text{ test speed, in m/s}
- \( R_{td} \) \text{ tactical diameter rating}
- \( R_{t\alpha_{10}} \) \text{ rating for the first overshoot angle in the 10/10 zigzag test}
- \( R_{t\alpha_{20}} \) \text{ rating for the first overshoot angle in the 20/20 zigzag test}
- \( R_{ti} \) \text{ initial turning ability rating}
- \( R_{ts} \) \text{ stopping ability rating}
- \( r \) \text{ rate of turning}

**STATISTICAL RATINGS**

Barr et al. (1981) performed statistical analyses of full-scale data from builder’s trials of more than 600 vessels. Based on this information, the authors proposed a system of criteria to judge the maneuverability of a vessel. These criteria were based on a rating level rather than on a conventional “pass-fail” approach. The mean values from the statistical analyses were assumed to represent average performance. Ratings “marginal”, “below average”, “above average” and “superior” were then assigned based on certain percentages of the standard deviation. The rating system included criteria for tactical diameter, the first overshoot angle, initial turning ability and head reach.

**TACTICAL DIAMETER**

The average tactical diameter \( TD_m/L \) measured in ship lengths was based on analyzing all the ships in a statistical sample (total 483 ships) from Barr et al. (1981), yielding the following formula:

\[
TD_m/L = (3.21 - 1.62 \cdot 10^{-6} \Delta)
\]

where \( \Delta \) is displacement in tons, the standard deviation of \( TD/L \) was taken as (value for all the ships from Barr et al. 1981).

\[
\sigma_D = 0.84
\]

Boundaries for the various ratings from Barr et al. (1981) are given in Table 2.

**Table 2 Rating Limits for Tactical Diameter**

<table>
<thead>
<tr>
<th>Rating Level</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>( TD_m/L ) -1.25 ( \sigma_D )</td>
<td>---</td>
</tr>
<tr>
<td>Above Average</td>
<td>( TD_m/L ) -0.5 ( \sigma_D )</td>
<td>( TD_m/L ) -1.25 ( \sigma_D )</td>
</tr>
<tr>
<td>Average</td>
<td>( TD_m/L ) +0.5 ( \sigma_D )</td>
<td>( TD_m/L ) -0.5 ( \sigma_D )</td>
</tr>
<tr>
<td>Below Average</td>
<td>( TD_m/L ) +1.25 ( \sigma_D )</td>
<td>( TD_m/L ) +0.5 ( \sigma_D )</td>
</tr>
<tr>
<td>Marginal</td>
<td>---</td>
<td>( TD_m/L ) +1.25 ( \sigma_D )</td>
</tr>
</tbody>
</table>

Formulae (1) and (2) with Table 2 allow calculating the boundaries for tactical diameter ratings in terms of ship length (see Figure 1). Taking into account that IMO requirements (IMO 2002a) limit tactical diameter to 5 \( L \), the following equations express the consistent criteria:

if \((4.26 - 1.62 \cdot 10^{-6} \Delta) < TD/L \leq 5\) then \( R_{td} = 1 \)

if \((3.63 - 1.62 \cdot 10^{-6} \Delta) < TD/L \leq (4.26 - 1.62 \cdot 10^{-6} \Delta)\) then \( R_{td} = 2 \)

if \((2.79 - 1.62 \cdot 10^{-6} \Delta) < TD/L \leq (3.63 - 1.62 \cdot 10^{-6} \Delta)\) then \( R_{td} = 3 \)

if \((2.16 - 1.62 \cdot 10^{-6} \Delta) < TD/L \leq (2.79 - 1.62 \cdot 10^{-6} \Delta)\) then \( R_{td} = 4 \)

if \((2.16 - 1.62 \cdot 10^{-6} \Delta) > TD/L \) then \( R_{td} = 5 \)

**Figure 1 Rating Limits for Tactical Diameter**

![Figure 1 Rating Limits for Tactical Diameter](image-url)
No special formulations are needed here as the constant in the 1st inequality in (3) is already less than 5, so a range for the rating 1 always exists.

**THE FIRST OVERSHOOT ANGLE**

The average first overshoot angle for both 10/10 and 20/20 zig-zag tests \( \alpha_m \) was based on analyzing all ships in the statistical sample (total 83 ships) from (Barr et al 1981), yielding the following formula:

\[
\alpha_m = (0.567 + 0.222Cb) \cdot \delta_R
\]  

(4)

Where \( Cb \) is a vessel block coefficient and \( \delta_R \) is an angle of rudder deflection in degrees, it is equal to 10 for 10/10 zig-zag test and to 20 for 20/20 zig-zag test. The standard deviation of \( \alpha_m/\delta_R \) was taken as \( \alpha = 0.35 \) (the value for all the ships analyzed in Barr et al, 1981).

The boundaries for ratings from (Barr et al 1981) are given in Table 3 and shown in Figure 2

![Figure 2 Rating Limits for the Non-Dimensional First Overshoot Angle](image)

Formal substitution of equation (4) and (5) into Table 3 leads to the following system of inequalities for 10/10 zig-zag test that are not necessarily consistent with the IMO requirements:

<table>
<thead>
<tr>
<th>Rating Level</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>( \alpha_m - \sigma_\alpha )</td>
<td>-</td>
</tr>
<tr>
<td>Above Average</td>
<td>( \alpha_m - 0.5 \sigma_\alpha )</td>
<td>( \alpha_m - \sigma_\alpha )</td>
</tr>
<tr>
<td>Average</td>
<td>( \alpha_m + 0.5 \sigma_\alpha )</td>
<td>( \alpha_m - 0.5 \sigma_\alpha )</td>
</tr>
<tr>
<td>Below Average</td>
<td>( \alpha_m + 1.25 \sigma_\alpha )</td>
<td>( \alpha_m + 0.5 \sigma_\alpha )</td>
</tr>
<tr>
<td>Marginal</td>
<td>-</td>
<td>( \alpha_m + 1.25 \sigma_\alpha )</td>
</tr>
</tbody>
</table>

if \( 10.04 + 2.22Cb < \alpha_{10} \),

then \( R\alpha_{10} = 1 \)

if \( 7.42 + 2.22Cb < \alpha_{10} \leq 10.04 + 2.22Cb \)

then \( R\alpha_{10} = 2 \)

if \( 3.92 + 2.22Cb < \alpha_{10} \leq 7.42 + 2.22Cb \)

then \( R\alpha_{10} = 3 \)

if \( 1.29 + 2.22Cb < \alpha_{10} \leq 3.92 + 2.22Cb \)

then \( R\alpha_{10} = 4 \)

if \( \alpha_{10} \leq 1.29 + 2.22Cb \)

then \( R\alpha_{10} = 5 \)

According to (IMO 2002a), the first overshoot angle in the 10/10 zig-zag maneuver should not exceed

- 10 degrees if \( L/V \) is less than 10 seconds
- 20 degrees if \( L/V \) is 30 seconds or more
- \((5+0.5L/V)\) degrees if \( L/V \) is between 10 and 30 seconds

Here, \( V \) is ship speed in meters per second corresponding to 85% of maximum continuous rating (MCR) of the engine. The above formulation is conveniently expressed in an auxiliary function form where:

\[
f_{10} \left(L/V\right) = \begin{cases} 10.0 & \text{if } L/V \leq 10 \, s \\ 5 + 0.5 \cdot \left(L/V\right) & \text{if } 10 \, \text{sec} < L/V < 30 \, s \\ 20.0 & \text{if } L/V \geq 30 \, s \\ \end{cases}
\]  

(7)

Theoretically, the maximum value for the boundary between ratings 1 and 2 could be 12.26 degrees (block coefficient cannot exceed 1), while the minimum value for the auxiliary function \( f_{10} \left(L/V\right) \) could be 10 degrees. This formulation does not allow using this function as an absolute maximum for the system of equations (6) for all cases without special provisions that are detailed below:

Rating for the first overshoot angle in a 10/10 test \( R\alpha_{10}=1 \) can be assigned only if:

\[
10.04 + 2.22Cb < f_{10} \left(L/V\right) \]  

(8)

where \( Cb \) is the block coefficient.

Provided that condition (8) is satisfied,

if \( 10.04 + 2.22Cb < \alpha_{10} \) \( : f_{10} \left(L/V\right) \)

then \( R\alpha_{10} = 1 \)

(9)

Provided that condition (8) is satisfied,

if \( 7.42 + 2.22Cb < \alpha_{10} \) \( : f_{10} \left(L/V\right) \)

then \( R\alpha_{10} = 2 \)

(10)

Provided that condition (8) is not satisfied,

if \( 7.42 + 2.22Cb < \alpha_{10} \) \( : f_{10} \left(L/V\right) \)

then \( R\alpha_{10} = 2 \)

(11)

Assignment of other ratings does not depend on condition (8) and is to be done according to the following formulae:
if \( 3.92 + 2.22Cb < \alpha 10_1 \leq 7.42 + 2.22Cb \)
then \( R\alpha_{10} = 3 \)

if \( 1.29 + 2.22Cb < \alpha 10_1 \leq 3.92 + 2.22Cb \) (12)
then \( R\alpha_{10} = 4 \)

if \( \alpha 10_1 \leq 1.29 + 2.22Cb \)
then \( R\alpha_{10} = 5 \)

Making criteria consistent with the IMO standard for the 20/20 zig-zag test is trivial as the minimum IMO requirement for the first overshoot angle of the 20/20 zig-zag test is 25 degrees, which is more than the theoretically possible value for the rating boundary, 24.43 degrees.

The following set of harmonized inequalities for the overshoot angle from the 20/20 zig-zag test is obtained as follows:

if \( 20.09 + 4.44Cb < \alpha 20_1 \leq 25 \)
then \( R\alpha_{20} = 1 \)

if \( 14.84 + 4.44Cb < \alpha 20_1 \leq 20.09 + 4.44Cb \)
then \( R\alpha_{20} = 2 \)

if \( 7.84 + 4.44Cb < \alpha 20_1 \leq 14.84 + 4.44Cb \) (13)
then \( R\alpha_{20} = 3 \)

if \( 2.59 + 4.44Cb < \alpha 20_1 \leq 7.84 + 4.44Cb \)
then \( R\alpha_{20} = 4 \)

if \( \alpha 20_1 \leq 2.59 + 4.44Cb \)
then \( R\alpha_{20} = 5 \)

The resulting overshoot angle rating is calculated as an average for both tests

\[ R\alpha = 0.5(\alpha 10 + \alpha 20) \] (14)

Formula (14) is based on the assumption that overshoot angles in 10/10 and 20/20 zigzag tests are equally important, as there are no data available to impose weights for these figures. The more frequently used 10 degree deflections could perhaps be somehow “equalized” by usage of 20 degree deflections in more serious situations like avoidance of grounding and collisions.

### INITIAL TURNING ABILITY

IMO requirements (IMO 2002a) use the time to reach 10 degrees course change in a 10/10 zig-zag test as a criterion for initial turning ability while the rating system (Barr, et al. 1981) uses the Norbin-Nomoto equation

\[ T' \cdot \dot{r'} + r = K' \cdot \delta_R \] (15)

Here, \( r' \) is non-dimensional yaw rate, \( \dot{r'} \) is a non-dimensional derivative of yaw rate, and \( T' \) and \( K' \) are the Norbin-Nomoto parameters. The Norbin-Nomoto equation is a result of further simplification of linear equations of motions in the horizontal plane (derivation details can be found in Lewis, 1989).

The parameter \( T' \) has physical meaning as a measure of hull inertia while \( K' \) could be considered as simply a rudder coefficient. In general, linear equations are only good for small amplitude motions. That is why the Norbin-Nomoto parameters \( K' \) and \( T' \) can be used as a measure of a vessel’s initial turning ability (deviation from the initial state is still small).

Barr, et al. (1981) used the inverse of these parameters \( K'^{-1} = 1/K' \) vs. \( T'^{-1} = 1/T' \) for the statistical analysis. This analysis yielded a curve of a mean relationship for the Norbin-Nomoto inverse parameters (see Figure 3).

\[ K'^{-1} = 0.625 + 0.375 \cdot T'^{-1} \] (16)

The data for the inverse Norbin-Nomoto parameter ratings were then broken down into ranges as shown in Table 4.

<table>
<thead>
<tr>
<th>Rating Level</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>-</td>
<td>1.25K' m</td>
</tr>
<tr>
<td>Above Average</td>
<td>1.25K' m</td>
<td>1.10K' m</td>
</tr>
<tr>
<td>Average</td>
<td>1.10K' m</td>
<td>0.90K' m</td>
</tr>
<tr>
<td>Below Average</td>
<td>0.90K' m</td>
<td>0.75K' m</td>
</tr>
<tr>
<td>Marginal</td>
<td>0.75K' m</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3 Rating Limits for Norbin-Nomoto Parameters

The Norbin-Nomoto equation (15) is an ordinary linear differential equation of the 1st order and therefore has an analytical solution. Neglecting the time of rudder deflection, the solution can be expressed as:

\[ r' = K' \cdot \delta_R \left( 1 - \exp \left( -\frac{r'}{T'} \right) \right) \] (17)

Here, \( r' \) is non-dimensional time.

The yaw angle can be expressed through the integration of equation (17):
\[
\psi(t') = K' \delta_R \left( t' - T' + T' \exp \left( - \frac{t'}{T'} \right) \right).
\]  

(18)

As the relationship between the Norbin-Nomoto parameters are defined through formula (16) and Table 5, the yaw angle and rudder deflection are defined to be equal to 10 degrees. The expression (18) becomes a nonlinear algebraic equation relative to non-dimensional time \( t \) expressed in ship lengths traveled, which is exactly the IMO criterion. Finally, the values from Table 4 are expressed in a form of ship lengths traveled before the 10 degree change of course is reached:

\[
\begin{align*}
\text{if} & \quad 2.24 < \frac{l_{10}}{L} \leq 2.50 \quad \text{then} \quad R_{ti} = 1 \\
\text{if} & \quad 2.07 < \frac{l_{10}}{L} \leq 2.24 \quad \text{then} \quad R_{ti} = 2 \\
\text{if} & \quad 1.89 < \frac{l_{10}}{L} \leq 2.07 \quad \text{then} \quad R_{ti} = 3 \\
\text{if} & \quad 1.63 < \frac{l_{10}}{L} \leq 1.89 \quad \text{then} \quad R_{ti} = 4 \\
\text{if} & \quad \frac{l_{10}}{L} \leq 1.63 \quad \text{then} \quad R_{ti} = 5
\end{align*}
\]

(19)

where \( R_{ti} \) is the initial turning rating.

STOPPING ABILITY CRITERIA

IMO requirements (IMO 2002a) and the maneuvering rating system (Barr, et al. 1981) use different criteria for stopping ability of a vessel, i.e., track reach and head reach, respectively. As a result, the rating criteria could only be formulated for head reach since there are no statistical results available for track reach in Barr, et al. (1981). Track reach adapted as IMO criterion is to be used as a minimum requirement.

The mean value for head reach in the rating system is accepted as:

\[
HR_m/L = Fn \cdot (43.0 + 0.000139 \cdot \Delta)
\]

(20)

where \( L \) is ship length in meters, \( \Delta \) is displacement in metric tons, \( Fn \) is Froude Number

\[
Fn = V/\sqrt{gL}
\]

(21)

where \( g \) is the acceleration of gravity (9.807 m/s\(^2\)), \( L \) is ship length in meters, and \( V \) is the test speed in meters per second.

The value of standard deviation of \( HR_m/L \) was taken from Barr et al. (1981) for all vessels in the database, without differentiation of ship types:

\[
\sigma_{HR} = 26.4
\]

(22)

The boundaries for the ratings from Barr et al. (1981) are given in Table 5 and Figure 4.

The formulae (21) and (22) along with Table 5 yield the following system of inequalities to express the rating criteria:

\[
\begin{align*}
\text{if} & \quad Fn (69.4 + 0.000139 \Delta) < HR/L \\
& \quad \text{then} \quad R_{ts} = 1 \\
\text{if} & \quad Fn (56.2 + 0.000139 \Delta) < HR/L \leq Fn (69.4 + 0.000139 \Delta) \\
& \quad \text{then} \quad R_{ts} = 2 \\
\text{if} & \quad Fn (29.8 + 0.000139 \Delta) < HR/L \leq Fn (56.2 + 0.000139 \Delta) \\
& \quad \text{then} \quad R_{ts} = 3 \\
\text{if} & \quad Fn (16.6 + 0.000139 \Delta) < HR/L \leq Fn (29.8 + 0.000139 \Delta) \\
& \quad \text{then} \quad R_{ts} = 4 \\
\text{if} & \quad HR/L \leq Fn (16.6 + 0.000139 \Delta) \\
& \quad \text{then} \quad R_{ts} = 5
\end{align*}
\]

(23)

The resultant rating is calculated as an average of all the individual ratings. This is equivalent to the assumption that all the maneuvering qualities are equally important.

\[
Rt = 0.25 \cdot (Rtd + Rta + Rti + Rts)
\]

(24)

This assumption was adopted as there is not sufficient data available for allowing a numerical ranking of the different maneuvering qualities in order to assign statistical weight to each of them.
Each of these individual ratings could only be assigned if the minimum requirement corresponding to the IMO standard is satisfied, so the average rating really measures quantitatively how the maneuvering performance exceeds the IMO standards.

INITIAL VALIDATION

To check how a vessel would be rated by the previously described system, a typical VLCC was chosen with the characteristics from the MARAD full-formed hull model test series (Roseman, 1987), so the result of these model tests could be utilized. The principal dimensions of the VLCC are given in Table 6.

Numerical simulation was calculated using the mathematical model and hydrodynamic coefficients from Roseman (1987), a detailed description of which can also be found in ABS (2006). The early stage design prediction technique by Lyster and Knight (1979) was used to predict the turning maneuver characteristic and the prediction of the stopping distances was done using the method recommended in IMO (2002b). Results of these simulations are summarized in the Table 7.

Table 6 Principal Dimensions of Sample VLCC

<table>
<thead>
<tr>
<th>Length $L_{BP}$, m</th>
<th>349.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadth molded $B$, m</td>
<td>58.3</td>
</tr>
<tr>
<td>Draft in full load $T$, m</td>
<td>19.4</td>
</tr>
<tr>
<td>Block coefficient, $Cb$</td>
<td>0.875</td>
</tr>
<tr>
<td>Displacement, metric tons</td>
<td>355600</td>
</tr>
</tbody>
</table>

No early stage design prediction was done for the zig-zag maneuvers and path stability tests, as there are no reliable methods available. The design speed was set for 15 knots.

As can be seen from Table 7, the recommended prediction methods gave good estimates of what can be expected in the later design stage with the exception of the stopping distance. All of the predictions have errors on the conservative side.

The results of the simulations were evaluated using the previously described rating system. The results are summarized in Table 8. As can be seen from that table, the maneuverability of the sample vessel was found to score above average (the calculated average rating was 3.8).

The form of the hull and stern configuration of the models of the MARAD series (Roseman 1987) are typical for tankers and bulk carriers designed and built in 70’s and 80’s. Vessels of this type have been in operation more than 30 years. Experience gained during their operation was used (along with experience with other types of vessels) in the development of IMO standards. A relatively high rating obtained by the sample vessel can be considered as indirect proof that past experience was properly reflected in the proposed rating system. However, more validation work is needed for confident practical application of the rating system.

Table 7 Predicted Maneuvering Results for a Sample VLCC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactical diameter (turning, rudder 35 deg), ship lengths</td>
<td>2.79</td>
<td>3.21</td>
</tr>
<tr>
<td>Advance (turning, rudder 35 deg), ship lengths</td>
<td>2.77</td>
<td>2.99</td>
</tr>
<tr>
<td>Velocity of steady turn (turning, rudder 35 deg), knots</td>
<td>5.33</td>
<td>5.79</td>
</tr>
<tr>
<td>Diameter of steady turn (turning, rudder 35 deg), ship lengths</td>
<td>2.73</td>
<td>2.41</td>
</tr>
<tr>
<td>First overshoot angle (10/10 zig-zag maneuver), degrees</td>
<td>11.06</td>
<td>-</td>
</tr>
<tr>
<td>Second overshoot angle (10/10 zig-zag maneuver), degrees</td>
<td>32.17</td>
<td>-</td>
</tr>
<tr>
<td>Distance traveled until the course reached 10 degrees, ship lengths</td>
<td>1.63</td>
<td>-</td>
</tr>
<tr>
<td>First overshoot angle (20/20 zig-zag maneuver), degrees</td>
<td>17.38</td>
<td>-</td>
</tr>
<tr>
<td>Second overshoot angle (20/20 zig-zag maneuver), degrees</td>
<td>20.0</td>
<td>-</td>
</tr>
<tr>
<td>Distance traveled until the course reached 10 degrees, ship lengths</td>
<td>1.67</td>
<td>-</td>
</tr>
<tr>
<td>Residual yaw rate (Pull-out maneuver), rad/s</td>
<td>0.0038</td>
<td>-</td>
</tr>
<tr>
<td>Height of instability loop (Direct spiral maneuver), rad/s</td>
<td>0.00545</td>
<td>-</td>
</tr>
<tr>
<td>Width of instability loop (Direct spiral maneuver), degrees</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>Track reach (Stopping test), ship lengths</td>
<td>9.7</td>
<td>13.8-18.3</td>
</tr>
<tr>
<td>Head reach (Stopping test), ship lengths</td>
<td>7.42</td>
<td>-</td>
</tr>
<tr>
<td>Lateral deviation (Stopping test), ship lengths</td>
<td>3.77</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 8 Evaluation of Maneuverability

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Simulated</th>
<th>Required</th>
<th>Result or Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance, ship lengths</td>
<td>2.77</td>
<td>4.5</td>
<td>Passed</td>
</tr>
<tr>
<td>Tactical diameter</td>
<td>2.79</td>
<td>3.05 &lt; Td ≤ 2.21</td>
<td>RdTd = 3</td>
</tr>
<tr>
<td>10/10 zig-zag 1&lt;sup&gt;st&lt;/sup&gt; overshoot angle, deg</td>
<td>11.06</td>
<td>9.36 &lt; α&lt;sub&gt;101&lt;/sub&gt; ≤ 11.98</td>
<td>R&lt;sub&gt;t&lt;/sub&gt;α&lt;sub&gt;10&lt;/sub&gt; = 2</td>
</tr>
<tr>
<td>10/10 zig-zag 2&lt;sup&gt;nd&lt;/sup&gt; overshoot angle, deg</td>
<td>32.17</td>
<td>α&lt;sub&gt;102&lt;/sub&gt; &lt; f&lt;sub&gt;101&lt;/sub&gt;(L/V) = 40</td>
<td>Passed</td>
</tr>
<tr>
<td>20/20 zig-zag 1&lt;sup&gt;st&lt;/sup&gt; overshoot angle, deg</td>
<td>17.38</td>
<td>11.725 &lt; α&lt;sub&gt;201&lt;/sub&gt; ≤ 18.725</td>
<td>R&lt;sub&gt;t&lt;/sub&gt;α&lt;sub&gt;20&lt;/sub&gt; = 3</td>
</tr>
<tr>
<td>Resulting overshoot angle rating</td>
<td>R&lt;sub&gt;t&lt;/sub&gt;α = 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance traveled until course change reaches 10 degrees during 10/10 zig-zag maneuver, ship lengths</td>
<td>1.63</td>
<td>l&lt;sub&gt;10&lt;/sub&gt; ≤ 1.633</td>
<td>R&lt;sub&gt;t&lt;/sub&gt;l&lt;sub&gt;10&lt;/sub&gt; = 5</td>
</tr>
<tr>
<td>Pull-out test</td>
<td>Vessel is straight-line unstable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width of instability loop, degrees</td>
<td>4.5</td>
<td>α&lt;sub&gt;U&lt;/sub&gt; &lt; 12</td>
<td>Passed</td>
</tr>
<tr>
<td>Track reach, ship lengths</td>
<td>9.7</td>
<td>TR &lt; 15</td>
<td>Passed</td>
</tr>
<tr>
<td>Head reach, ship lengths</td>
<td>7.42</td>
<td>HR ≤ 8.7</td>
<td>Rts = 5</td>
</tr>
<tr>
<td>Resultant rating</td>
<td>3.875</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FUTURE DEVELOPMENT**

Development of a rating system capable of quantifying maneuvering performance and consistent with IMO maneuvering standards does not solve all of the problems of assuring adequate maneuvering capabilities.

Current measures of maneuverability are based on vessel experience at full speed in deep, unrestricted waters. The assumption taken is that if a vessel shows good maneuvering performance under these benchmark conditions, then her maneuvering performance will also be good at slow speed and in restricted waters, i.e., where good maneuvering performance is most needed.

The validity of this assumption is built upon historical experience and therefore loses credibility when considering new vessels of innovative design. Therefore, one of the desirable directions for future development would be improving methods of prediction of maneuvering qualities in shallow and/or restricted waters, and at slow speeds. Wind is another factor that can have significant influence on maneuverability, especially for vessels with large windage areas. Appendix 1 contains a brief review of research efforts in these directions.

Consideration of maneuvering under these more challenging conditions may require development of another set of trial maneuvers. Information on this topic is reviewed in Appendix 2.

Analysis of the relative importance of the different maneuvering qualities may be one of the directions for future research. This problem may not have a simple solution and some maneuvering qualities could be more important than others for particular types of vessels or operations (e.g., stopping ability for a VLCC). Also, for the same vessel, the relative importance of various maneuvering qualities may vary for different situations (e.g., yaw checking while maneuvering in restricted waters vs. path stability while underway in deep unrestricted waters). One of the possible ways to quantitatively assess the relative importance of various maneuvering qualities could be to undertake a survey among pilots and navigators, similar to what was done in (Barr, 1990).

Another line of prospective development lies in the field of application of Nonlinear Dynamics. Nonlinear Dynamics is a relatively new branch of applied mathematics with its main focus on the study of the behavior of nonlinear dynamical systems. The latter is understood as a system of nonlinear ordinary differential equations of the first order. Nonlinear Dynamics from the applications perspective is a set of formal computational methods which allow finding and identifying all possible modes of behavior while systematic changes of a given set of control parameters are performed.

The interest in Nonlinear Dynamics as a tool for maneuverability evaluation seems to be quite natural as maneuvering equations have to be nonlinear in order to get results of engineering utility. The methodology for applying numerical simulation to maneuvering has been more or less established for conventional vessels. The appearance of novel types and especially high-speed vessels may, however, require new approaches.

So far, there have been several successful attempts of application of Nonlinear Dynamics in hydrodynamics of ships:

- Dynamical stability in beam seas
- Surging and Surf-Riding in following seas
- Parametric roll resonance
- Broaching.
Among these applications, broaching is most directly of interest to the subject of this paper, as the phenomenon occurs in the boundary between maneuverability and dynamic stability. A brief review of Nonlinear Dynamics applications to broaching is given in Appendix 3

CONCLUSIONS

The main focus of the paper has been an effort to combine a consistent Criteria Rating System (Barr et al 1981) with IMO Standards (IMO 2002a). The resulting system of rated criteria has IMO standards as a minimum and gives an additional credit for achieving better maneuverability performance.

The paper also looks beyond the rating system, reviewing ways of future development of maneuvering standards and looking into the effects of restricted waters, slow speed maneuvering, and other issues.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation and sincere gratitude to all individuals and organizations that contributed to the development of this paper and the Guide on Vessel Maneuverability.

In particular, the role of Jim Card has to be especially recognized as “an engine” empowering the entire project. Contributions from H. Yu, J. Spencer and B. Menon were also very important in formulating the maneuvering requirements. Comprehensive review and detailed comments made by P. Alman, R. Barr, D. Gray, A. Landsburg L. Kobylinski and K. Spyrou were very useful and helpful. The discussions and comments from the SNAME H-10 panel are highly appreciated, in particular, contributions from its members including L. Vest, M. Morris, J. Mazurkiewicz and R. Sedat.

The authors are grateful to members of the management and staff of ABS, who contributed to this project, in particular: G.Benzi, C.Baker, R.Conachey, D.Dietrich, J.Kokarakis, S.Maryuama, D.McCafferty, K.MeSweeney, J.Palfy, A.K.Seah, Y.S. Shin, K.Tamura, M. Zuccarelli. The comments and reviews from industry were also very helpful; these comments were received from DSME, IHI, Kawasaki Shipbuilding Corp., SHI, Shin Kurushima, and USC.

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APPENDIX I REVIEW OF MANEUVRABILITY PREDICTION AT SLOW SPEED, AND IN WIND, AND SHALLOW/RESTRICTED WATERS


Taking shallow water into account seems quite logical as canals and port approaches do have depth limitations. It is also known that the influence of the bottom can be significant on hydrodynamic forces and maneuvering performance.

Most ports themselves have shallow water, often requiring dredged channels, as ships are usually built to maximize use of the depth available. Thus, taking shallow waters into account seems a very logical next step.

Using a simplified analysis formulation based solely upon slender body theory, one can approximately predict how a vessel’s maneuvering derivatives change when operating in shallow water as compared to deep water. Clarke, et al (1982) has provided expressions for the ratio of shallow water maneuvering derivatives to deep water values. Using these expressions it is possible to evaluate the effect of reduced water depth on the vessel’s path stability and steady turning diameter. However, additional validation work would be needed to use these data as a background for new standards.

Roseman (1987) contains specific maneuvering model test data for a systematic series of full-formed ships tested at various water depths.

Although restricted waters may also be important, the number of cases to consider makes it impractical to consider a general case or all cases in a comprehensive manner. However, there are a variety of techniques to consider some aspects of the maneuvering in restricted waters (see e.g., Norrbin, 1971).

Although all vessels may experience extreme wind at some time during their lifetime, wind effects are particularly important for vessels with a large above water area as compared to their immersed lateral plane area. Specific vessel types typically have large above water lateral plane areas. These include car carriers and cruise ships, however, other vessel types such as tankers at ballast draft and heavy lift vessels carrying particularly large cargos may also exhibit large above water lateral plane areas.

A rule of thumb which has been suggested by Barr, et al (1981) as a result of an extensive series of simulations considers if the ratio of the above water...
lateral plane area, \( A_s \), to the below water lateral plane area, \( A_e \), and the ratio of the square of the ratio of the ship speed \( V_{\text{ship}} \) to wind speed, \( V_{\text{wind}} \) exceeds 125, i.e.,

\[
\left( \frac{V_{\text{wind}}}{V_{\text{ship}}} \right)^2 \times \frac{A_w}{A_s} \geq 125
\]

Then, consideration of wind effects should be taken into account for the maneuvering prediction. There are at least two sources of published techniques to assess the effect of wind on ship turning and these are Isherwood (1971), and OCIMF (1994). The Isherwood method is derived from the analysis of 107 wind tunnel tests of all types of merchant ships while the OCIMF data concentrates on VLCC’s. Unfortunately, both methods have limitations and so one must also be familiar with wind tunnel testing techniques (e.g., SNAME T&R, 1983 and 1988) to more accurately determine wind effects for a particularly unique ship design. In this work, only the ability of the rudder to correct a wind-induced sway and yaw was investigated. Clearly, additional requirements of both captains and port authorities might also need to be investigated in this area. Again, account of wind in maneuvering standards is still a thing of the future.

The effect of reduced speed on a vessel’s maneuvering characteristics is an important consideration in evaluating a vessel’s critical maneuvering performance. The non-dimensional stability derivatives are assumed to be constant over a wide range of speeds. Therefore, captive maneuvering model tests to determine maneuvering derivatives are typically only performed at the design speed. However, this does not imply that path stability or steady turning characteristics do not change with speed. Quite the contrary, a vessel’s path stability is typically reduced when forward speed is increased.

According to Strom-Tejsen and Chislett, (1966), the non-dimensional forces and moments, which depend upon the sway and yaw accelerations, do not change much with speed. Furthermore, the static drift angle and yaw velocity also do not vary appreciably up to a certain critical speed, which is typically higher than the design speed of most low to medium speed merchant ships. However, as the ship speed increases beyond this critical speed the non-dimensional forces will vary. This variation is due to the sinkage and trim of the hull, which the vessel may experience at and beyond this critical speed. The same cannot be said about the forces and moments due to the rudder. This is due to the fact that the flow over the rudder cannot be characterized by the flow around the ship hull at a point but instead is accelerated due to the propeller. Although maneuvering experiments are typically performed at only one speed, typically, the design speed. Care must be taken in utilizing results at this speed for predictions at other speeds, especially if the design speed is quite high. The non-dimensional forces are different if significant sinkage and trim differences exist between the design speed and the low maneuvering speed. Moreover, the rudder angle coefficients must also take into account the correct flow over the rudder.

Unfortunately, the Strom-Tejsen and Chislett, (1966), results are based upon a single general cargo ship design and more research needs to be done investigating the effect of reduced speed on maneuvering of modern high-speed ships such as container ships (SNAME, 1989) and also on low speed full-form ships. Generally speaking, modern, full-form tankers and bulk carriers are path unstable at design speed but are often path stable at a lower speed due to the speed dependence of the path stability. This also affects the turning ability of the ship, making it hard to turn at lower speed since the ship may become more path-stable.

Moreover, Roseman (1987) contains specific maneuvering model test data for a systematic series of full-formed ships tested at various speeds, including turning circle and zig-zag performance. Although Roseman’s results are for a finite number of speeds, they have been completed for a systematic series of full-form hulls.

The effect of changing speed on the maneuvering performance needs to be further studied in order to come up with a well-grounded proposal for standards.

**APPENDIX 2 REVIEW OF ADDITIONAL TRIAL POSSIBILITIES**

At the same time, in order to gain a better understanding of a vessel’s maneuvering performance at slow speed and in shallow water and possibly restricted waters, additional ship trials are recommended. Hwang, et al (2003) co-authored a paper at the MARSIM 2003 conference which surveys the need for additional trials and recommends an extensive listing of additional trial possibilities.

The trials reviewed by the Hwang, et al (2003) include a maneuver called “back and fill” which essentially consists of a backing and turning exercise much in the manner an automobile would perform a K-turn.

A reduced list involving the variations of the standard IMO trials, i.e., turning circle, spiral (if the ship is path unstable), zig-zag, and stopping maneuver but at slow speed and in shallow water may be recommended. Also, trials investigating the effect of acceleration and deceleration (Bishop, et al, 1975) on maneuvering performance may be recommended.

Additional trials for slow speed and shallow water could be turning circles. Although the speed is something that the trials crew can control, the shallow water is not. The speed tests should be done at half ahead and slow speeds and the shallow water test should be done in water depths exceeding the draft by only 20 to 50 percent if such water is accessible.

Additional trials such as an accelerating turn and coasting turn may also be useful in assessing the vessel’s maneuvering performance and are relatively simple to implement. There has also been discussion of
the so-called Minimum Effective Rudder (MER) criterion. The MER is just the rudder angle at the width of the instability loop for a path unstable ship in shallow water and at slow speed. Obviously, this also needs to be quantified for a path unstable ship.

In addition, if a thruster is installed it may be prudent to test the thruster’s performance at various speeds in order to quantify the loss in effectiveness of the thruster as the vessel’s speed increases.

A summary of additional trials for shallow water and slow speed maneuvering found in literature is given below:

1. Turning circle at half speed and slow speed.
2. Turning circle in shallow water (depth and draught ratio is less than four and as low as 1.2 to 1.5).
3. Accelerating and coasting turning circle.
4. If ship is path unstable in shallow water or at slow speed: Assess Path Instability in Shallow water and at slow speed (at least half speed and slow speed but additional speeds if warranted).
5. Zig-zag in shallow water and at slow speed standard 20/20 zig-zag may have to be modified to consider 5/5 zig-zag.
6. If a thruster is installed: Thruster performance at zero speed, slow speed and additional speeds.
7. If a vessel normally operates at very different drafts such as a tanker at full load and ballast draft, additional maneuvering trials should be performed at both drafts.

APPENDIX 3 REVIEW OF NONLINEAR DYNAMICS APPLICATIONS TO BROACHING ANALYSIS

The mechanics of ship broaching are of interest to both the controllability and seakeeping analysis disciplines. Broaching is defined as a phenomenon that results in a ship not being able to maintain its course despite the application of the maximum steering effort (Umeda and Renilson, 1992). An attempt to summarize the essential information on broaching was done by one of the authors in Belenky and Sebastianov (2003) and a review is presented here.

The most commonly used mathematical model of broaching today was formulated in the early 90’s and includes 4 degrees of freedom: surge, sway, roll and yaw as well as autopilot equations (Umeda and Renilson, 1992 and 1994). The maneuvering equations contain some terms of the second order and have to be complemented with wave forces. Comparison of the model tests with calculations have shown that wave diffraction forces may have a significant contribution in sway and yaw (Umeda, et al 1995). Further investigation of the phenomenon of broaching was done using captive model testing for broaching simulation by Hashimoto, et al (2003). Surge, sway and yaw coupling are included into the rolling equations developed. The study is limited to regular waves.

Nonlinear dynamics assumes a standard sequence of study of this model that first has to be presented as a system of ordinary differential equations of the first order, further referred to as a dynamical system. The first step is a search for equilibria for the practical range of the control parameters. These studies were done for both unsteered and steered vessels by Spyrou (1995 and 1996). For an unsteered vessel, rudder deflection and Froude Number were chosen as control parameters. In the case of a steered vessel, the rudder deflection angle was determined by an autopilot commanded course. Equilibrium in this case means riding the surf, which is the prerequisite for a broaching.

The next step is to look at the stability of these equilibria and study possible modes of ship motion in the vicinity of these equilibria and then investigate large motions. The large motions could be limit cycles or periodic motions (periodic surging could be used as an example), or escape-type motions that actually are the means to broaching.

Spyrou (1996) found that for different scenarios of broaching:

1. The ship is involved in periodic surging while speed is increased. At a certain speed periodic surging ceases to exist and the only possible state is surf-riding, which could be unstable. The unstable equilibrium may push the system in yaw direction, which is the broaching situation.
2. A ship may be “caught” in stable surf-riding equilibrium. An attempt to escape from such a situation by changing speed and course does not necessarily lead to periodic surging again, but could provoke broaching.
3. Gradual increase of commanded heading may lead to oscillations of rudder deflection and changing of heading in quite large limits, which also will be perceived as broaching.
4. Periodic motions were found to be capable of bifurcation caused by significant nonlinearity of the system, which resulted in a dramatic increase of yaw amplitude. This also falls into the definition of broaching.

Spyrou (1997) reported that some of these broaching scenarios may be prevented by the proper choice of autopilot gains.

Another aspect of broaching is the possibility of capsizing due to extremely violent turn. The study by Umeda, (1999) is mostly focused on the outcome of broaching. This study was supported by a number of model experiments (Umeda, et al, 1999), (Umeda and Hamamoto, 1999) and it was finally used as a theoretical background for the design of an anti-broaching device (Umeda and Matsuda, 2000).
**Discussion**

**Phillip Alman, Member**

I would like to thank the authors for the opportunity to comment on their paper. The central issue is how to design, verify and develop a rating for maneuvering performance. This paper outlines how the authors went about incorporating the rating concepts into an ABS guide, and what can be done to provide a level of assurance that a ship will satisfy those requirements. Development of a rating system for maneuvering was a central issue twenty years ago when Lincoln Crane was chairman of Panel H-10 and we are still having the same discussion today. This paper will help to refocus one of the central issues of ship controllability, and provide a re-examination of where we have come in the intervening years.

Some of the major milestones in the development of maneuvering standards have been the following:

- **1978** – Port and Tanker Safety Act (48 USC 391a) (Mandating controllability requirements)
- **1979** – CG Report CG-M-4-79, “Report to the President on Evaluation of Services and Technologies to Improve Maneuvering and Stopping Capabilities of Large Vessels”
- **1981** – Hydronautics Inc Report to CG “Technical Basis for Maneuvering Performance Standards”
- **1985** – MSC/Circ.389 “Interim Guidelines for Estimating Maneuvering Performance of Ships”
- **1987** – IMO Resolution A.601(15) “Provision and Display of Maneuvering Information on Board Ships”
- IMO Resolution A.751(18) “interim Standards for Maneuverability of Ships”
- Panel H-10 “Maneuvering Design Workbook”

One can see that there has been a continued movement toward improved controllability of ships spearheaded by both SNAME Panel H-10, USCG, and internationally through IMO. Quite clearly the ABS guide will add its place to the list of milestones above and needs to be considered in that context.

In their paper the authors note that tactical diameter, first overshoot angle, initial turning ability, and stopping ability are each assigned an equal rating. The authors note that the overall rating criteria is an average of the parameters measured, and that the assumption was made because there was insufficient data to allow the assignment of a statistical weight to each. I have some concerns about this approach in that it is likely too simplistic to capture the complex nature of ‘good’ ship controllability.

However, let’s set aside any discussion over the technical merits of the proposed rating system for a moment. The paper is silent on how this rating system or any rating adds value in practice as a measure of good controllability and in so doing one is left with the question: What does this add to safety? How do the authors envision such a rating system could be used for classification, port safety, training or improved ship design? I believe that in order to establish the technical merits of a maneuvering rating you must also have a vision for how it will be implemented. How does the rating system enable the ship owner to reduce risk? What could be done in the classification process to acknowledge the benefit a higher rating? Does it make sense to have a rating system for a criteria representing deep water performance when we all acknowledge that the biggest ship handling risks are in shallow congested water? Is the rating system as it is presently put forth correctly weighting the most important performance parameters and should these parameters be weighted the same for all ships? How does a marginal rating influence training requirements? Tug requirements? I wonder if the authors could address these points a little further.

The development of maneuvering standards, have been focused on providing measures for mitigating risks associated with poor controllability in congested harbor approaches where there is the highest risk of accident. Many times these risks are heightened not so much by a ship with marginal controllability characteristics but by a pilot who is unfamiliar with the ship he is trying to bring into a tricky harbor, and the lack of good bridge communication and information. IMO Resolution A.601(15) is an example of a stepping stone to address those specific risks. In contrast, the issue of broaching in heavy seaways, while of concern, has to be considered in the context of heavy weather shiphandling/dynamic stability and those associated risks. Consequently I would caution against blurring the focus of the worthwhile discussion of this paper with issues related to heavy weather ship handling and dynamic stability.

**Serge Sutulo, Visitor**

It is my pleasure to congratulate the authors with this extensive paper reminding everybody that the maneuvering standardization problem is a never ending story and the proposed rating scale, although being definitely just the “zero” approximation, can become useful as a reference point. Meanwhile, the following comments could probably help in the future work in this area.
1. Any rating system encouraging reach of ultimate maneuvering performance will not necessarily result in safer sailing especially in dense-traffic areas such as canals, port approaching waterways etc. If some ship is capable to perform extremely (i.e. far above average) tight turns and/or stop at a very short distance, she will sooner or later produce an unexpected sharp maneuver creating a dangerous situation (an analogy: think about the rear of a car with the stopping distance equal, say, to one third of a typical stopping distance). Also, the human factor may contribute unfavorably: a navigator in control of a super-maneuverable vessel can become victim of excessive self-confidence, relax too much and allow some negligence. From this viewpoint, the minimum standard approach adopted by IMO seems to be even more reasonable, at least for merchant ships, as it stimulates the shipbuilders and ship owners to meet the limiting requirements with minimum margin which can gradually reduce the variance numerical values of the maneuverability indices corresponding to different vessels. Of course, these limiting standards must be re-considered from time to time so that the natural technological progress be not hampered.

2. The first-order Nomoto equation can be indeed, as the authors mentioned, obtained from the full linearized ship mathematical model but the ship time lag $T'$ and the ship gain $K'$ will then often have numerical values very different from those obtained by Barr et al. (1981) and shown on Fig. 3. In the latter case, the Nomoto equation was used as an input-output model whose parameters $T'$ and $K'$ were obtained from zigzag tests by means of an identification procedure. It can be noticed that all the values shown on Fig. 3 are positive while calculating the same parameters from the formal linearized models often results in negative $T'$ and $K'$ corresponding to directionally unstable ships which constitute a considerable part of the world fleet. This discrepancy happens because adequate mathematical models of the overwhelming majority of surface displacement ships are substantially nonlinear and the linearized models' parameters depend heavily on the linearization method and on the dimensions of the state-space domain over which the linearization was performed (see Sutulo 1998 for details). For instance, if $T'$ and $K'$ are estimated after a 10′–10′ zigzag, the equation (15) will satisfactorily describe the ship's behavior in the same zigzag but, very likely, will bring very poor predictions for, say, 2′–2′ and 30′–30′ zigzags. Hence, when talking about linearized mathematical models including the Nomoto model (15), it is always necessary to specify how exactly the linearization is made. However, as the parameters $T'$ and $K'$ (or their inverse values) can both vary over a very wide range, they are not so convenient for standardization. Much more stable is the ratio $K'/T'$ having the meaning of an equivalent initial dimensionless angular acceleration of the ship after an instantaneous rudder deflection by the 1rad angle. More details on this and some related issues can be found in (Sutulo 1995).

3. It is doubtless that certain requirements to the maneuvering qualities of ships and, seemingly, of many other craft and vehicles depend on the craft's reference time $T_{ref} = L/V$. However, the character of this dependence as it is assumed in the IMO Standards and described by eq. (7), leaves some questions unanswered. While the linear dependence on $T_{ref}$ in the interval from 10s to 30s is more or less expectable, flat standards at $T_{ref} > 30$s and, especially, at $T_{ref} < 10$s do not look natural. While this is not so important with the minimum criterion value approach adopted by IMO, it will be definitely much less consistent in connection with any rating-based standards. In fact, the alternative stability criterion based on the spiral curve hysteresis loop’s width (IMO 2002b) treats $T_{ref} = 10$s as the separation point between the directionally stable and unstable ships. As the loop width is zero for all stable ships, this parameter cannot be used for any more stable standardization at $T_{ref} < 10$s. But bearing in mind that the loop width can be interpreted as a measure of the spiral curves' nonlinearity, an obvious consistent generalization can be introduced. Although no direct proofs have been presented so far, there are strong reasons to believe that the smaller is $T_{ref}$ of any craft controlled by a human operator, the more linear its static characteristic (represented by the spiral curve in the case of the horizontal-plane maneuvering of ships) must be. A more detailed discussion on this subject is presented in (Sutulo 1995). As to the zigzag overshoot angles, their standardized values should likely decrease further at $T_{ref} < 10$s although at present no definite requirements can be formulated and further studies are necessary. Finally, it must be noted that not so many merchant displacement ships do really have $T_{ref} < 10$s and this can explain a relatively small interest of IMO to this range. However, $T_{ref} = 6$–8$s is common for naval displacement vessels like frigates or nuclear-powered submarines and the rating-based approach will be likely the most suitable exactly for this class of ships.
Additional References


Frans Quadflieg, Member

Thank you for the attempt to write nuances to the maneuvering criteria. I agree that maneuvering criteria should not be considered as on/off or good/bad, as they are some ways in between. In particularly this is the case because ‘good’ or ‘acceptable’ maneuvering behavior is subjective. The ratings are based on “what conning officers” expect from ships, or otherwise “what pilots expect as normal behavior”.

There are a couple of assumptions made which one can discuss. These assumptions are:

1. Assume that when the behavior is acceptable in deep water, it is acceptable in shallow water
2. The ‘Barr’ statistics are based on conventional ships, and (as time goes by) these ship forms used for the statistics are old-fashioned ships. But they are representative to what pilot would consider average ships.
3. All factors St have the same weight, as the average weighting factor is determined as the average.

It is about the last item that my question goes on this subject. Often, a vessel having poor course keeping ability has small turning circles. As such, a vessel can have an overshoot angle close to IMO criteria and a very small turning circle (say 2 ship lengths). In the present proposal, this vessel would (on the average) have a good rating: it would have a 1-rating on overshoot angle and a 5-rating on turning circle. Averaging a 3, giving a nice value. However, a pilot might still have difficulties with it, compared to a vessel which has 3 on overshoot angle and 3 on turning circle. My question is therefore. Could we bring this method further in 2 ways:

1. Assume some penalty function when a rating 1 is occurring. This should then also be based on what pilots or conning officers think is really important, i.e. do they rate the stopping ability by reversing the engine equally important to turning ability or course keeping ability?
2. Apply this method to for example all ships typically entering Houston ship channel, and see whether the Houston pilots agree with this rating. A clear correlation should be found before this is applicable.

Furthermore, the term “path stability” is used in the appendices. Could you explain this?

Another question is about the literature overview on the broaching. I think there are a couple of more articles well related to the subject, and the STAB conferences are a good forum where many thin gs are discussed. However, I get the feeling that a 4 degrees of freedom mathematical model is used as the basis for that. I would pose that this is insufficient. A 6 degrees of freedom model is the least (as the 7th degree of freedom could be the autopilot and/or the ride control system). I would like to hear the authors’ opinion on this, as well as how captive tests could fill in gaps of knowledge. But above all, let me say that I agree that much more work is needed to understand and describe the phenomena related to course keeping in waves.

Konstantinos Spyrou, Member

This work fills a gap in ship maneuverability assessment as it sets up a system of reward for those ship owners and shipyards who are interested, rather than satisfying marginally the IMO standards, to build ships with superior maneuvering qualities.

More than fifteen years ago the discusser had advocated the development of an overall rating system for ship maneuverability. At that time a hierarchical tree had been built that, at its lowest level, contained a selected set of measures of performance. Each one of these measures had to reflect some maneuvering quality of a distinctive nature. Weighting factors were then assigned in the various branches of the assessment tree, determined from a suitable matrix of preferences.

To ensure immediate compatibility with the IMO standards, the authors have opted for a simpler structure in their rating system. I consider that the tactical diameter, the first overshoot, the length traveled before a 10° heading change and the head reach during stopping represent a set of sufficiently distinctive maneuvering qualities and in this respect they are a good basis for the assessment. Perhaps the possibility of varying the weights, depending on priorities per ship type, makes sense and it could be considered in future amendments of the ABS guide.

Certainly, after the application of the rating procedure a lot of experience about ship performance will be collected. Combined with the fact that hull-form designs evolve in time, it seems essential that the rating limits are reviewed from time to time in order to ensure that they reflect the true condition or the world fleet.

The point that the authors make about the necessity of assessing ship maneuverability in shallow/restricted waters, wind and waves is indeed timely. Perhaps these matters could be considered more seriously at regulatory level. Although the nonlinear nature of ship behavior in these environments make the analysis to seem complex for the traditionally educated naval architect, not to mention the serious difficulties concerning mathematical modeling, it seems that the current state-of-the-art allows for a step forward in this direction.
Once more I would like to congratulate the authors for undertaking this influential work.

**Lech Kobylnski, Visitor**

In my opinion establishing a system of rating for maneuverability of ships is a good idea. In particular such system may show how much a particular ship is better from the point of view of handling than the minimum level required by the IMO standards set up by the resolution MSC 137(76).

The main point is that the particular ship must satisfy IMO requirements. But better rating will result in increased safety level against CRG accidents (collisions-rammings-groundings). However in my opinion the matter is more complicated as apparently is considered in the paper, that, to my mind, should be considered as interim proposal. This in particular applies to the overall rating (refer to formula 24). True enough, as the Authors stated, currently are no data available to allow for the attaching weights to different maneuvering qualities, so the only way out is to assume that all weights are equal one.

Obviously, however, the importance of different maneuvering characteristics from the point of view of safety is different. Moreover some of the characteristics are related to each other and some are not. For example, overshoot angle in zig-zag test is related to dynamic stability, hence to the width of loop in spiral test, if the ship is dynamically unstable. Also, the turning ability (assessed by the advance and tactical diameter) is related to the course keeping ability (assessed by overshoot angles and, in case, by the width of instability loop), but stopping ability (assessed by the head reach in crash stop) is another, in general, the better turning ability, the worse course keeping ability and vice versa, although some measures could be taken to improve both. Therefore, for different types of ships the importance of those characteristics is different and the same overall rating may result in rather different assessment of capabilities for those ships. For example one can imagine a ship having excellent turning and course keeping characteristics highly rated but poor stopping characteristics (assessed by head reach in crash stop) that could lead to rather low overall rating. However for some ships this might be misleading, especially for ships fitted with special rudders where stopping could be achieved by other maneuvers. I do not see any good solution for this problem at the moment, but it seems to me that the matter requires further study.

In overall rating only tactical diameter was included, not advance. But advance is equally important. In general the smaller advance, the smaller tactical diameter, so this might be justified. But it is not always so. With installation of special, patented rudders, for example Schilling rudder, this is not justified, and it seems to me that both characteristics have to be taken into account.

The rating for different maneuvering characteristics is based on the standard deviation calculated from the static analysis performed by Barr et al in 1981 that created the basis for development current IMO criteria. That was more than 25 years ago when IMO requirements did not exist. It seems that this may be a week point, because after IMO requirement were introduced newly built ships in general might reveal better maneuvering characteristics as designers attempted to satisfy those requirements. Therefore the statistical sample should include ships constructed after IMO requirements were introduced. I realize, however, that such statistical data at present do not exist.

The above observations must be referred to the future studies, because at present there is apparently not possible to take them into account. The only purpose of my comments is to point out that the matter should not be considered as closed and the rating system should be further investigated and possibly improved in the future.

**Roderick A. Barr, Member**

The authors have described a particularly valuable step in process of developing a rational basis for evaluating the inherent maneuverability of ships. As the author’s note in their Introduction, the IMO “Standards for Ship Maneuverability” carry no weight of International law since these standards have not been made part of SOLAS. Rather, these standards are recommended for adoption by national authorities in member countries. The U. S. Coast Guard has promulgated these standards for informational purposes only, with no requirement that ships adhere to the IMO standards, leaving any need to adhere to these standards to actions of classification societies such as the ABS, or to economic pressures such as those generated by insurers.

Political and economic pressures within the IMO permitted the adoption only of standards reflecting minimally acceptable performance. The authors describe the development of a set of numerical ratings which are both consistent with the IMO minimum performance standards and provide a rational quantitative basis for rating maneuvering performance between “0” (failing to meet the IMO standards) to “5” or “superior.” While there are many limitations to this process, as discussed by the authors, the recommended rating system represents an important step beyond the limited IMO standards and toward a not yet attainable and wholly rational methodology for assessing ship maneuvering performance and safety.

The authors use as an example for application of the ABS rating system, a ship from the shallow draft hull series tested at Hydronautics and described by Roseman ( ), and indicate that this hull has an above average rating of 3.8. This relatively high rating is not surprising in view of the concern paid to maneuverability in the development of the series hull form and rudder apertures.
Critical maneuvering usually occurs at low speeds and in harbors and restricted waterways, and thus at conditions for which the IMO standards and the authors ratings are not directly applicable. Characterization of low speed maneuvering in restricted waters remains an elusive goal. In Appendix 2 the authors suggest a number of non-standard trials including turning with water depth-draft ratios (H/T) of 4 and 1.2 to 1.5. Typically the effect of water depth is small at H/T = 4, and based on water depths usually now encountered in harbors and waterways, it would be more appropriate to conduct any shallow water trials at depth-draft ratios of 1.2 and 1.5 to 2.0, which will facilitate the estimation of maneuvering at other water depths of interest.

With regard to low speed maneuvering and conduct of non-typical maneuvers such as coasting and accelerating turns and zig-zag maneuvers, special note should be taken of the deep and shallow water trials of the Esso Osaka described by Crane (1979).

I congratulate the authors on a most interesting and valuable paper.

Additional References


John C. Daidola, Member

The authors are to be commended for their efforts to continue to focus on merchant ship maneuverability even as IMO standards have been adopted. There was a time when ship maneuverability was not significantly considered in the design spiral, but we are now at a point where it is an established element. Improving on this can only be positive considering the potential impact on safety as our shipping lanes and harbors become ever more crowded.

The authors have acknowledged the lengthy period associated with the development of the IMO standards. This can be expected as the development of international standards requires the agreement of many parties with differing experiences and points of view. Nevertheless, the establishment of these standards has been a milestone and an advance for merchant ship design and safety.

In considering additional performance requirements and criteria it will be important to remain cognizant of these same potentially differing experiences and points of view. The authors’ approach of incorporating the IMO requirements within the bounds of their rating system provides a logical step from which to measure improvements. At the same time, as these have already been agreed upon, the consideration of additional or more stringent requirements can be built on a solid foundation understood by all interested parties.

One potential issue with a “rating” system is that by definition it identifies one vessel as being more maneuverable than another. As maneuverability is an issue of safety and has been at the center of some very serious accidents, have the authors given consideration as to how the establishment of such a system may have an impact on legal issues and litigation? I believe it will be important to give this attention as to not create a situation where designers, shipbuilders and ship owners will be placed at risk for categorically not targeting the highest rating.

As another example of the interest in improving maneuverability above more or less established bases, the NATO NG-6 Specialist Team on Maneuverability has developed a set of target maneuvering criteria for naval vessels based on type and mission. These have been established by operator preferences rather than historical design experience. The intent is for member nations to consider these criteria in new shipbuilding programs and provide feedback on what has been achievable.

Congratulations to the authors on their contribution.

Bruce L. Hutchison, Fellow

I extend my congratulations to the authors on an interesting paper that presents a creative approach to the cause of advancing both awareness of ship maneuvering qualities and promoting the improvement of those qualities.

Other discussers have likewise noted, and in some cases questioned, the uniform weighting of the various components of the maneuvering characteristics vector used to produce the scalar rating. I would like to suggest that the importance and relative weighting of the characteristics is likely to be port and waterway specific. While the authors’ approach is appropriate for an overall vessel rating for a vessel potentially engaged in worldwide trade, the components of the maneuvering characteristics vector may be of interest to the pilots in different ports. It is quite possible that the pilots in specific ports might ultimately arrive at their own, port specific, weighting vector that best captures the relative importance of the component characteristics within the context of their port. It would assist this secondary application if the component characteristics of calling ships were readily available to the pilots.

The rating system promoted by this paper may be readily determined from acceptance maneuvering trials in deep water. However, maneuvering is of the greatest consequence in shallow and restricted waters. Conceivably some additional rating and class notation might eventually evolve for maneuvering in shallow water. That too could be achieved based on maneuvering trials in shallow water. The problem of maneuvering in channels of restricted width (including the problem of meeting vessels) is more difficult though no less worthy of future attention.
A number of the other discussers have mentioned the need to adjust the weighting factors to be more appropriate for the controllability needs of particular ship types and sizes. They have also noted the need to develop criteria and standards based on shallow and restricted water operations which are where most maneuverability problems are likely to occur. The maneuverability community has been struggling with these issues and other restricted modeling related questions for decades without a lot of success. The fact is that our current modeling techniques are based on full scale test data acquired in deep water. Adjustments are then made to these models to account for restricted water effects including banks and other restrictions. Ship maneuverability characteristics are highly nonlinear in other than deep water, however. Gathering data on full scale ships in shallow and restricted waters from which to validate modeling improvements has rarely been performed because of the high cost and difficulty. There are essentially only the full scale tests from the \textit{Esso Osaka} described by Crane\textsuperscript{3} from which to validate trajectory prediction models developed from model tests and theory. Thus there is indeed a lot of work still to be done.

I just wanted to add, however, that \textit{NOW} is the time to act as we finally have the opportunity to advance the state of the art! Dual frequency DGPS receivers with an additional local broadcast signal provided yield very accurate ship location information both horizontally and vertically (within a few centimeters). This capability provides us at last with the tools necessary to gather accurate full scale data in restricted waters. Never before have we really been able to know where the ship is located with enough accuracy to be able to validate models with the accuracy necessary to reflect bank and bottom effects in shallow and restricted waters. Panel H-10 (Ship Controllability) guided the development of an extensive set of full scale data gathering tests sponsored by the U.S. Corps of Engineers in the Houston ship channel a couple of years back with this technology to gather systematic information with which to validate existing models. In exploration of the data, however, it is clear that we can’t simply validate the existing models we have been using but must do some additional ground work with more advanced models and additional full scale validation tests to advance the state of the art to where it needs to be.\textsuperscript{4}

With reasonable cost data gathering and modeling tools now available it is time to begin the further work that is necessary. All that is needed is some expanded interest and financial support in this area to complete the job (hopefully a major accident won’t be required!). Continued rapid trade growth in our ports demands our efforts to develop effective models and set appropriate criteria to reduce the probability of an accident from restricting cargo movements which can be economically disastrous.

I congratulate the authors on a most interesting and valuable paper. With everyone’s interest and help we can advance the state of the art and provide the criteria and accurate modeling capabilities needed!

\textbf{Authors’ Closure}

The authors would like to thank all of the nine written discussion participants for their reviews, interesting ideas and thoughtful comments, specifically on the paper and generally on the state of the art. The authors are particularly grateful to the SNAME H-10 Panel.

Overall, the discussion participants generally agree that a rating system, which gives credit for improved maneuverability is superior to the IMO Pass/Fail criteria. However, many believe that equal weighting as provided by equation (24) can be improved upon.

As a way to achieve this, it is proposed by the discussion participants to implement weights for each rating based on expert estimates (F. Quadvlieg) and/or specific for ship types (L. Kobylinski) and/or routes and harbors (B. Hutchison). All of these ideas are definitely worthwhile and deserve further development. This development, however, may be enhanced once the experience of application of the proposed rating system is collected and analyzed (K. Spyrou). The authors strongly agree with this point of view.

Concerns were expressed that the vessels used in the rating system may not be representative of current building and recently delivered hulls although representative of the existing operational fleet. R. Barr noted that the high rating of 3.8 for the Hydronautics hull series is to be expected since much attention was paid to the maneuvering characteristics of these hulls.

As far as modern hull forms are concerned, there is an ongoing effort to evaluate the ratings for several recent hull forms, based on numerical simulation. Available data are placed in Table 1, below:

Initial results seem to indicate that these new building vessels are generally above average in their maneuvering rating; although not enough data is yet available to make concrete conclusions whether these vessels are representative of all new buildings.


P. Alman raises the question of how the rating system is meant to be implemented. At this moment, the rating system is part of two ABS optional class notations “MAN” and “MAN-A”. Both these notations are offered to ship owners as a proof of compliance with IMO standards. All vessels with rating 2.5 and above are eligible for the optional notation “MAN-A” that could also be used as recognition of or a credit for enhanced maneuverability performance. These class notations are optional, meaning that ABS-classed vessels do not have to have them. Request for these notations is completely at the ship owner’s discretion. Further advancement of the rating system will substantially depend on industry response.

Table 1 Results of maneuvering simulation and rating evaluation for modern hulls

<table>
<thead>
<tr>
<th>Hull Type</th>
<th>Containership</th>
<th>Containership</th>
<th>Bulk Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, B.P., m</td>
<td>282</td>
<td>200</td>
<td>182</td>
</tr>
<tr>
<td>Breadth, m</td>
<td>32.2</td>
<td>32.2</td>
<td>32.2</td>
</tr>
<tr>
<td>Draft amidships, m</td>
<td>12.1</td>
<td>11.7</td>
<td>12.3</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>0.645</td>
<td>0.61</td>
<td>0.823</td>
</tr>
<tr>
<td>Displacement, tons</td>
<td>72,700</td>
<td>45,800</td>
<td>60,860</td>
</tr>
<tr>
<td>Tactical diameter (-)</td>
<td>2.3</td>
<td>2.94</td>
<td>2.92</td>
</tr>
<tr>
<td>RTD</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>10/10 1st overshoot, deg</td>
<td>3.95</td>
<td>5.85</td>
<td>16.4</td>
</tr>
<tr>
<td>Rtx1</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>20/20 1st overshoot, deg</td>
<td>10.53</td>
<td>12.62</td>
<td>19.85</td>
</tr>
<tr>
<td>Rtx2</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>10 deg course change distance (-)</td>
<td>2.5</td>
<td>2.5</td>
<td>1.71</td>
</tr>
<tr>
<td>Rti</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Head reach (-)</td>
<td>7.36</td>
<td>8.49</td>
<td>6.91</td>
</tr>
<tr>
<td>Rts</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total rating</td>
<td>3.4</td>
<td>2.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>

A. Landsurg suggests the need for full-scale validation, emphasizing new opportunities as accurate GPS instruments have become widely available. The authors strongly agree with this point of view and furthermore believe that correlation of predictions and full-scale trials is very important for improving ship maneuverability. Using modern tools such as GPS, especially in combination with voyage data recorders (VDR), not only during the trial but also in channels and harbor approaches creates a technical possibility for gathering a substantial amount of valuable data on ship maneuvering, including cases of shallow/restricted water and slow speed.

This brings another aspect of the problem raised during the discussion of this paper, the limits of existing unrestricted and deep water, design speed and deep draft maneuvering criteria. This is a general concern in the maneuvering field. The authors agree with the point of view expressed by R. Barr that this is a difficult and most “elusive problem”.

The hope exists, however, that the solution can come from new instruments as pointed out by A. Landsburg and above. Creation of port/approach/channel specific data sets and rating systems as suggested by B. Hutchison may be the way to go (localized criteria for restricted maneuvering/slow speeds and global or generic criteria for unrestricted waters and service speeds).

The authors agree with J. Daidola that the development of international standards is a long process; decisions sometimes are a result of a compromise as parties involved may have very different experience and points of view. As a result, technical and non-technical limitations may be imposed on the resulting criteria. These limitations were inherited by the rating system; it is a consequence of its compatibility with IMO standards. From another side, risk is always involved with implementation of the new criteria. The authors believe that in the case of the rating system, a risk is not greater than the risk associated with any other performance-based criteria, as the rating system generally follows the trend in that direction.

Several questions were related to mathematical models and definitions used in the paper. Dynamic stability is generally referred to as path stability but more accurately it is straight-line stability, i.e., the ship will return to a straight path but not necessarily the same initial path.

The authors agree that the linearization leading to the Norbin-Nomoto 1st order equation (S. Sutulo) has to be treated with caution as a dynamical system describing ship motion in a horizontal plane is substantially nonlinear and results of linearization may have only limited application.

As far as the broaching model is concerned, a model with four degrees of freedom plus autopilot equation is considered to be the minimal set of equations needed to reproduce broaching in stern quartering seas; and as a minimal set, it has the
advantage of simplicity that makes it a preferable tool for qualitative study.

The authors agree that the human element is an important factor for any control problem, including handling of a vessel. The focus of this particular paper was on hydrodynamic and dynamical aspects of this problem. The general objective in this area is to design a vessel with the best controllability; human reaction on the improved controllability was not a subject of this paper. At the same time, the authors strongly believe that better controllability contributes to enhanced safety of shipping.