Abstract—The integrated sailing performance is important to the ship design and manufacture. However, it is very hard to be evaluated objectively and reasonably. In this paper the evaluation system of integrated sailing performance of ship’s was built which included seakeeping performance, wave loads, speed and stability performance in waves. The main characters were picked out and considering the influence of wave environment to build the evaluation system. AHP method was used to get the weight factors, and then the evaluation system could be built. So, the effects of wave and wind could be considered in the evaluation system. And then the evaluation system would be better than the single performance evaluation system and the evaluation system in calm water. The research of this paper is important to the integrated sailing performance evaluation system and evaluating method, which laid the foundation for the next step in the establishment of the comprehensive navigation performance evaluation equation for the ships in the waves.

Keywords- integrated sailing performance of ship’s; wave ; evaluation system; index; AHP method

I. INTRODUCTION

The comprehensive navigability of the ship in waves has always drawn attention from the shipbuilding circles. With the concepts of energy conservation and environment protection as well as green shipbuilding deepening, people show more interest in the comprehensive navigability of the ship. However, the ship navigates at sea, which may be affected by waves during the process of navigation, so it is uncertain for the ship with an excellent navigability in the still water to possess equal performance in waves. The motion performance of the ship in waves is quite different from that in the still water. The ship motion caused due to stormy waves will bring great adverse effect on the work of people and use of equipment on the ship, reducing the comprehensive operating efficiency of the ship by a large margin. International Maritime Organization (IMO) stipulates that Energy Efficiency Design Index (EEDI) has been applied to new ships since 2013. The calculation formula of EEDI takes the influence of waves on the navigational speed into account, but many transport ships of our country fail to meet the average index. Once it is applied, it will make domestic ship industry suffer from a great loss, putting forward higher requirements on the comprehensive navigability of domestic ships in waves.

Currently, the evaluation systems on the navigability of the ship mainly focus on the still water and seldom consider the influence of waves, besides, most evaluation systems are established based on single performances, such as rapidity, seakeeping, and control ability and so on, forming a big gap with the actual comprehensive navigability of the ship. This paper establishes a comprehensive navigability index system of the ship in waves by taking various performance parameters of the ship in waves as characteristic parameters. Then, it adopts analytic hierarchy process (AHP) to make an analysis on each evaluation index by analytic hierarchy in classification to determine the parameters of each characteristic and the weights of each single index, so as to establish the comprehensive navigability index system of the ship in waves.

II. SELECTION OF EVALUATION INDEXES

Through analyzing the influence of each single index on the navigability of the ship and its task, etc. to select the seakeeping, wave load, rapidity and stability in waves and other properties based on the principles of completeness, independence, simplicity, scientificness and operability according to the degree of influence, while each index contains a number of related characteristic parameters, and then, to reasonably select those with great influence on the system performance as evaluation indexes through analysis.

A Rapidity Index

The rapidity of the ship refers to the ability of navigating at a certain speed under rated power of the engine. Generally, it includes ship resistance and ship propulsion. Admiralty coefficient [3] is an important
parameter measuring the rapidity of the ship, including
general information of the ship's good or bad performance
of resistance and propulsion, and also a comprehensive
evaluation factor for the rapidity of the ship. The formula
of admiralty coefficient is as follow:

\[ C_{m}(x) = \Delta^{-2/3} \cdot V_{s}^{-3} \cdot P_{K}^{0.6} / (\eta_{P} \cdot \eta_{H} \cdot \eta_{R}) \]  

(1)

where: \( \Delta \) ——Displacement;
\( V_{s} \) ——Speed in waves;
\( P_{K} \) ——Efficient power;
\( \eta_{P} \) ——Efficiency of propeller in open water;
\( \eta_{H} \) ——Efficiency of ship hull;
\( \eta_{R} \) ——Relative rotary efficiency;

Refer to the admiralty coefficient the speediness indexes
were taken as follows: Speed in waves, Efficiency of
propeller in open water, Efficiency of ship hull, and
Relative rotary efficiency.

B. Seakeeping Index

The seakeeping of the ship is determined by multiple
fundamental seakeeping factors. At present, it is generally
recognized at home and abroad that seakeeping factors
include 6-DOF motion, linear (angular) speed, and linear
/angular) acceleration, seakeeping incidents like water on
deck, propeller emergence, bow slamming and so on, and
the rate of seasickness. As mentioned above, the
seakeeping criterion of the ship has a direction relation
with the type, task, personnel quality and functions of
systems (equipment) of the ship. Different tasks require
different systems to work normally and effectively, so it is
difficult to set an absolutely unified criterion for each
seakeeping factor. Therefore, to reduce factors in
discussion through combining compatible items and
eliminating items with less effect according to the
circumstances. According to the result of materials I have
searched, survey on the navigator and performance of the
ship, this paper selects six seakeeping factors for the
comprehensive evaluation equation of seakeeping, namely
rolling, pitching, heaving, bow section slamming at one
station, water on deck and vertical acceleration of bow.

C. Stability Index

The stability of the ship refers to the ability of
returning to the original balanced position from the tilted
position resulting from the force of external torque after it
disappears. Static stability can be measured by the size of
the restoring torque, while dynamic stability needs to be
measured by the work of restoring torque. Both of them
are variables, and affected by water discharge, stability
height and roll angle of the ship. Although all ships built
go through the test conducted by the administration of
ships survey before launching, and put into service after
confirming to meet the stability standard, since there is a
close relation between the transverse stability of ships and
the complex marine environment, ships motion, operation and
other factors, while the weather criterion in the
existing stability standard is a quasi-dynamic method
based on the stability of ships in the still water and
statistical information. Thus, there are obviously problems
which need to be improved, including how to describe the
effects of wind, wave and flow on the ship correctly.
According to the research on ship stability in Chapter 1
and referring to the stability standard, this paper selects the
ability of wind resistance of the ship in stormy waves as
the evaluation index.

D. Wave Load Index

The longitudinal strength is mainly considered when
selecting performance indexes of [35] the wave load.
Generally, the analysis on longitudinal strength of the ship
contains two parts, including joint normal stress check and
shearing stress check when longitudinal bending and
ultimate stress check. The former two sections intend to
discuss the strength of ship when navigating in the normal
state, while the latter part intends to discuss the strength
reserve of ship in the unexpected state. Ships may suffer
from various unexpected conditions when using, such as
stranding, collision, underwater explosion and so on.
Since it is difficult to determine the external load applied
on the ship at this time, generally, the ultimate bending
moment is adopted to evaluate the carrying capacity of
ship structure.

From the existing specification for ship of our country, the
definition of ultimate bending moment \( M_{U} \) refers to that
in the flange plate of beam away from the cross section
and axis at utmost when internal stress reaches severe
stress (for stretching situation, it refers to the yield limit of
materials \( \sigma_{y} \); while for compressing situation, it refers to
the critical stress of grillage \( \sigma_{g} \)). That is:

\[
\begin{align*}
\text{Saggin} & \quad M_{s} = \min \left( \sigma_{r, \text{ deck}} W_{1 \text{ deck}}^{1/2} \cdot \eta_{1} \sigma_{W_{1 \text{ hull bottom}}} \right) \\
\text{Hogging} & \quad M_{h} = \min \left( \sigma_{r, \text{ hull bottom}} W_{2 \text{ hull bottom}}^{1/2} \cdot \eta_{2} \sigma_{W_{2 \text{ deck}}} \right)
\end{align*}
\]  

(2)

In the formula: \( W_{1 \text{ deck}} \) and \( W_{1 \text{ hull bottom}} \) ——are the section
moduli of deck and hull bottom when sagging
respectively;
\( W_{2 \text{ deck}} \) and \( W_{2 \text{ hull bottom}} \) ——respectively are the section
modulus of the deck and hull bottom under hogging
condition (when calculating the modulus mentioned above,
the effect of the losing stability of parts of panels should
be taken into account under the compressive stress);
\( \sigma_{r, \text{ deck}} \) and \( \sigma_{r, \text{ hull bottom}} \) ——respectively are the critical stresses when the plate frame of the deck and ship bottom
is under the overall bending;
\( \eta_{1} \) and \( \eta_{2} \) ——respectively are the ratio between the distance
from the hull girder tensile flange plate to the neutral axis
and the distance from the compression wing plate to the
neutral axis in the sagging condition and the hogging
condition (when the ratio is more than 1, 1 is taken).

The ultimate strength conditions are usually shown by
the non-dimensional ratio between the limit bending
moment and the maximum external bending moment
when in the normal navigation. That is, it must meet
whether in the vertical state or the hogging condition:
In order to make all the analysis findings reasonable, after constructing the judgment matrix, the consistency of the judgment matrix needs to be checked to ensure the too great deviation will not occur. That is, as for the judgment matrix, the following formula should be met when calculating:

\[ AW = \lambda_{\text{max}} W \]  

Among them, the \( A \) is the judgment matrix, \( \lambda_{\text{max}} \) is the greatest characteristic root of the matrix \( A \), and the \( W \) is the corresponding standardized eigenvector of \( \lambda_{\text{max}} \). After the normalized processing, it is the single taxis of hierarchy values (the weights) of the relative importance of the corresponding influence factors in the level to the last hierarchy factors. The consistency check of the single taxis of hierarchy is calculating the deviation consistency indexes:

\[ CI = \frac{\lambda_{\text{max}} - n}{n - 1} \]  

Among them, \( CI \) is the consistency index, and the \( n \) is the order number of the judgment matrix. When the random consistency ratio is:

\[ CR = \frac{CI}{RI} < 0.10 \]  

Then it is thought that the findings of the single taxis of hierarchy have the satisfactory consistency, that is, the judgment matrix \( A \) meets the requirement of consistency; if not, the judgment matrix needs to be adjusted to make it possess the satisfactory consistency. Among them, the \( RI \) is the random consistency index; its value can be obtained by looking up the table.

After judgment matrix possesses the satisfactory consistency, the corresponding eigenvectors after the normalization can be taken as the normalized weight values \( \lambda_{\text{max}} \).

B. The establishment of the index weight judgment matrix

The two-level index system is created by using AHP, taking the four performances-rapidity, seakeeping, stability and the wave loads as level 1 index, as shown in Table 2; The different evaluation indexes in each single performance are taken as level 2 indicators, and judgment matrices are respectively created according to the relative importance degree of each indicator, as shown in Table 3 and Table 4:

### Table I. Judgment Matrix Structure

<table>
<thead>
<tr>
<th>R</th>
<th>A1</th>
<th>A2</th>
<th>...</th>
<th>An</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>a11</td>
<td>a12</td>
<td>...</td>
<td>a1n</td>
</tr>
<tr>
<td>A2</td>
<td>a21</td>
<td>a22</td>
<td>...</td>
<td>a2n</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>An</td>
<td>an1</td>
<td>an2</td>
<td>...</td>
<td>ann</td>
</tr>
</tbody>
</table>

Among them, the \( a_{ij} \) means to \( R \), the importance of \( a_i \) to \( a_j \). In AHP, the evaluation of \( a_{ij} \) adopts 1, 3, 5, 7, 9 scaling method, making the comparison between two elements quantized. After the establishment of judgment matrix, the normalized processing and the consistency check are also needed. Set \( a_{ij} = f(u_i,u_j) \), then the judgment matrix should have the following characteristics:

\[ a_{ii} = 1 \]  

(4)

\[ a_{ij} = \frac{1}{a_{ji}} \quad (i, j = 1, 2, ... , n) \]  

(5)

\[ a_{ij} = \frac{a_k}{a_r} \quad (i, j, k = 1, 2, ... , n) \]  

(6)

In the Tables, \( A_1 \)- stability, \( A_2 \)- rapidity, \( A_3 \)- seakeeping, \( A_4 \)- the wave loads. The eigenvectors after being calculated and normalized \( W=(0.0994, 0.28397, 0.51794, \ldots) \).
the random consistency ratio CR=0.00156 < 0.10, which meet the requirement of consistency.

<table>
<thead>
<tr>
<th>TABLE III.</th>
<th>JUDGMENT MATRIX OF SPEEDINESS</th>
</tr>
</thead>
</table>
| \( A_2 \)   | \( \begin{array}{ccccc} w_1 & 1 & 5 & 5 & 5 \\
| w_2 & 1/5 & 1 & 1 & 1 \\
| w_3 & 1/5 & 1 & 1 & 1 \\
| w_4 & 1/5 & 1 & 1 & 1 \\
| \end{array} \) |

In the Tables: w 1- the navigational speed in waves, w 2- open water efficiency of the propeller, w 3- hull efficiency, w 4- the relative rotation efficiency. The eigenvectors after being calculated and normalized W 2=(0.625, 0.125, 0.125, 0.125)T the random consistency ratio CR=0 < 0.10, which meet the requirement of consistency.

<table>
<thead>
<tr>
<th>TABLE IV.</th>
<th>JUDGMENT MATRIX OF SEAKEEPING</th>
</tr>
</thead>
</table>
| \( A_3 \)   | \( \begin{array}{ccccccc} u_1 & 1 & 1/3 & 1 & 2 & 3 & 5 \\
| u_2 & 3 & 1 & 1/2 & 2 & 3 & 5 \\
| u_3 & 1 & 1/3 & 1 & 2 & 3 & 5 \\
| u_4 & 1/2 & 1/2 & 1/2 & 1 & 3 & 5 \\
| u_5 & 1/3 & 1/5 & 1/3 & 1 & 2 & 5 \\
| u_6 & 1/5 & 1/6 & 1/5 & 1/5 & 1/2 & 1 \\
| \end{array} \) |

In the Tables: u 1- the pitching, u 2- cross rolling, u 3- fluctuations, u 4- the vertical acceleration of the bow, u 5- the section attack on the bow one station, u 6- the water on deck. The eigenvectors after being calculated and normalized W 3=(0.18841, 0.37121, 0.18841, 0.14962, 0.06359, 0.03876)T the random consistency ratio CR=0.03322 < 0.10, which meet the requirement of consistency.

IV. THE CRITERIA VALUES OF EACH INDICATOR
A. The criteria of rapidity
Due to the existing resistance added by the waves, a certain speed loss occurs when the watercrafts sailing in the wind and waves. Taking the navigational speed in still water as the criterion, the comparison between the actual speed of the ship and the criterion value under the same main engine power is conducted.

B. The criteria values of the seakeeping
As for the criteria values of the seakeeping, there are different suggestions from different organizations as well as different scholars [1], and this article adopts a set of criteria values of the seakeeping proposed by China Ship Scientific Research Center, as shown in Table 5:

<table>
<thead>
<tr>
<th>TABLE VI.</th>
<th>CLASSES OF STABILITY OF SHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability Class</td>
<td>Wind Class</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

The wind resistant level of the ships in water with the normal drainage volume should accord with the provisions of Table 7.

<table>
<thead>
<tr>
<th>TABLE VII.</th>
<th>WIND RESISTANT LEVEL OF SHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement ( \Delta/t )</td>
<td>2500≤ ( \Delta )</td>
</tr>
<tr>
<td>Wind class</td>
<td>12</td>
</tr>
</tbody>
</table>

The wind resistant capability of the ships in water should accord with the formula:

\[ U_1 \geq U_0 \]  \quad (10)

In the formula:

- \( U_1 \) — the limit wind speed that the ship can bear, m/s
- \( U_0 \) — the rated gust wind speed that the ship can bear, m/s

The limit wind speed \( U_1 \) that the ship can bear (from a height 10m above the water); can be calculated by the following formula:
In the formula: $C$ — coefficient, $C = 115.5$;
$C_h$ — The correction coefficient of the wind speed distributed along the height, when $Z > 3.5m$,
$C_h = \left(\frac{10}{Z_s}\right)^{1/8}$; and $Z_s \leq 3.5m$, $C_h = 1.140$;
$I_C$ —— The minimum capsizing lever of the ship, $m$;
$\Delta$ — Calculating and checking the drainage volume in the loading state, $t$;
$A_h$ — The area exposed to the wind, $m^2$;
$Z$ — Calculating the wind action arm, $m$; as for the combat vessels, taking $Z = Z_s$;
$Z_s$ —— he distance from the shape center of the area exposed to the wind to the waterline, $m$.
When conducting the evaluation of the wind and waves environment adaptability aiming at a particular ship, the wind resistance level should be designated according to its drainage volume.

**D. The wave loads criteria**

According to the Ship General Specification [9], the ultimate strength conditions of the given ship should meet:

$$\frac{M_s}{M_s + M_w} \geq 2.6$$

(12)

Then, the evaluation system could be described in the following graph:

![Structure Graph of Evaluation System](image)

**V. Conclusion**

This article took the ship seakeeping, the wave load, rapidity and stability in the waves as well as the single characteristic parameters contained in each performance as the comprehensive navigation performance evaluation indexes for the ships in the waves, established the two-level index judgment matrix by using the AHP, obtained the weights of each indicator and determined the criteria for each indicator, which laid the foundation for the next step in the establishment of the comprehensive navigation performance evaluation equation for the ships in the waves.

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