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EVALUATION OF WIND AND WAVE ENVIRONMENT ADAPTABILITY OF SHIPS

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Summary

The environment adaptability of ships, especially integrated sailing performance in rough sea, is very important. In this paper an evaluation index system and a method of wind and wave environment adaptability of ships were proposed. The relative importance of the given indices was analyzed, and the weighting coefficients of the indices were given by estimation matrices. Also, an evaluation equation was developed. The AHP method and the method based on fuzzy theory were used for evaluating the environment adaptability of a hybrid monohull and a round bilge monohull. Furthermore, the effect of different models and weighting coefficients given by different matrices on the evaluation results was analyzed. The research indicated that the selection of evaluation parameters had a great influence on the evaluation results, and defining of the weighting coefficients was a difficult, but also a critical point for the evaluation of environment adaptability of ships.

Keywords: *environment adaptability; ship; evaluation; estimation matrix; fuzzy theory*

1. Introduction

Wind and wave environment adaptability of ships refers to the real response of ships to the wind and wave environment encountered in the actual sailing process. The wind and wave environment adaptability will become an important index in the evaluation of the comprehensive navigation performance of ships. Over the years, considerable research has been done in this field. Thus, Olson (1978) made a prominent contribution in terms of seakeeping performance evaluation. He proposed taking the percent of time that a ship can expect to operate in the environment as the evaluation index. The Japanese began to use the voyage data recorder to record the actual motions of ships in wind and waves to assess the safety of the ships in the 1990s. Shi Aiguo (1991) studied the influence of ships' performance in wind and waves on the sailing speed and course. He used the sailing speed in wind and waves, seakeeping performance, stability, and wave loads as the indices to establish the evaluation equation and evaluate the sailing performance so as to guide the sailing ships to choose a reasonable course and sailing speed. Yang Songlin (2003) used the genetic algorithm and the fuzzy optimization method, aiming at the rapidity and manoeuvrability in still water to make ship type fuzzy comprehensive optimization and use the result in the design of large medium-speed ships. Munehiko Minoura (2004) proposed a random theory model of studying seakeeping performance evaluation to evaluate the long-term statistics of ships' seakeeping performance by studying the response data measured in the actual sailing process of container ships and bulk carriers. Mao Xiaofei (2005) used the fuzzy comprehensive assessment method, seakeeping performance evaluation equation and other methods to make research on the evaluation index system of ships' seakeeping performance and manoeuvrability, and established an evaluation index system and evaluation method. Kadir Sariöz (2005) studied the influences of seakeeping performance evaluation criteria on passenger comfort evaluation based on the ISO standard.

The above overview of the carried out research shows that the key to the evaluation of the wind and wave environment adaptability of ships is to build a reasonable evaluation index system and choose a scientific index measurement and evaluation method. This paper presents a wind and wave environment adaptability evaluation index system for ships and uses the Analytic Hierarchy Process (AHP) method and Fuzzy Comprehensive Assessment (FCA) method to evaluate and analyze the wind and wave environment adaptability of ships.

2. Study on environment adaptability evaluation index system for ships

The construction of the evaluation index system must be based on the overall understanding and concept analysis of the evaluation system performance, i.e. the function and performance analysis of the system should be done first so as to determine which parameter can be defined in the quantitative form, and which parameter is requested by the system or subsystem performance index, and which indices may not be considered in the analysis and construction of the index system. Constructing the evaluation index system shall follow the principles of completeness, independence, conciseness, scientificity and operability. This paper presents the evaluation index system of wind and wave environment adaptability of ships constructed according to the above principles.

2.1 Construction of a two-layer evaluation index system

Firstly, the wind and wave environment adaptability of ships is decomposed into the first layer of performance indices such as rapidity in waves, seakeeping performance, maneuverability in waves, stability in wind and waves, wave loads and other performances as the first level of evaluation index. Secondly, the extraction for the second level of performance indices is started. The quantity of indices engaged in the evaluation is simplified by considering the maneuverability of the index system.

(1)Rapidity

The admiralty coefficient is an important parameter in the evaluation of rapidity of ships, including the comprehensive information on ship resistance and propulsion performance. It is a comprehensive evaluation factor of ship's rapidity. The admiralty coefficient formula is defined as follows:

$$C_{sp}\left(x\right)=\Delta^{-2/3}\cdot V_s^{-3}\cdot P_E/\left(\eta_O\cdot\eta_H\cdot\eta_R\right) \tag{1}$$

where: Δ − displacement, V_s − sailing speed in waves, P_E − effective power, η_0 − propeller open water efficiency, η_H − hull efficiency, η_R − relative rotation efficiency.

With reference to the admiralty coefficient, and adding the influence of wave environment on the basis of the original still water performance indices, the rapidity evaluation index is selected as, V_{sw} sailing speed in waves, η_{0w} propeller open water efficiency in waves, $\eta_{Hw,}$ hull efficiency in waves , and $\eta_{Rw,}$ relative rotation efficiency in waves.

(2) Seakeeping performance

The seakeeping performance factors include six degrees of freedom (three translations and three rotations) with respect to velocity and acceleration, waves on deck, propeller emergence, bow slamming, and rate of seasickness. For the seakeeping performance evaluation index in this paper six seakeeping performance factors are chosen: roll angle φ, pitching angle θ, heave amplitude Z, slamming probability P_{Imp} at section of bow 1 stand, deck wave frequency X and vertical acceleration amplitude at bow A_f.

(3) Stability

The influence of wind and waves on ships' stability is mainly presented in the change of the righting arm, resonant rolling at dead ship state, wind at transverse rotation side and other phenomena related to the control. Since the stability theoretical calculation method in wind and waves is not very perfect, and there is no definite stipulation in the specification, this paper, based on the research progress on ship stability, and with reference to the current stability specification, selects U, the wind resistance in waves of ships, as the evaluation index of the wind and wave environment stability.

(4) Maneuverability

Due to the diversity of maneuvering performance and its measurement index, and the contradiction among each maneuvering performance, the discontinuity and lack of additivity caused by the difference of maneuvering performance index and magnitude as well as the one-sidedness of maneuvering performance index measurement have brought difficulties to maneuverability evaluation. This paper proposes four basic maneuvering performance indices of ships: straight line stability, turning ability, brake stability and low speed sailing. It considers their respective measures from the intuitive viewpoint as: course stability index, relative turning diameter, relative braking distance, and the minimum operating speed to maintain the steering efficiency.

(5) Wave loads

The hull's longitudinal overall strength analysis usually includes two parts, i.e. composed normal stress and shear stress verification in total longitudinal bending, and ultimate strength verification. This paper uses the ultimate strength condition as the wave loads evaluation index.

The ultimate strength condition generally uses the dimensionless ratio m of limit bending moment and maximum bending moment in normal navigation, both for sagging and hogging condition as follows:

$$\frac{M_u}{M_s + M_w} \geq m \quad (m = \text{constant}) \tag{2}$$

where: M_s – bending moment in still water, M_w – bending moment in waves, M_u – limit bending moment.

Based on the above analysis, the second level of the evaluation index system of ships' wind and wave environment adaptability is constructed, Figure 1.

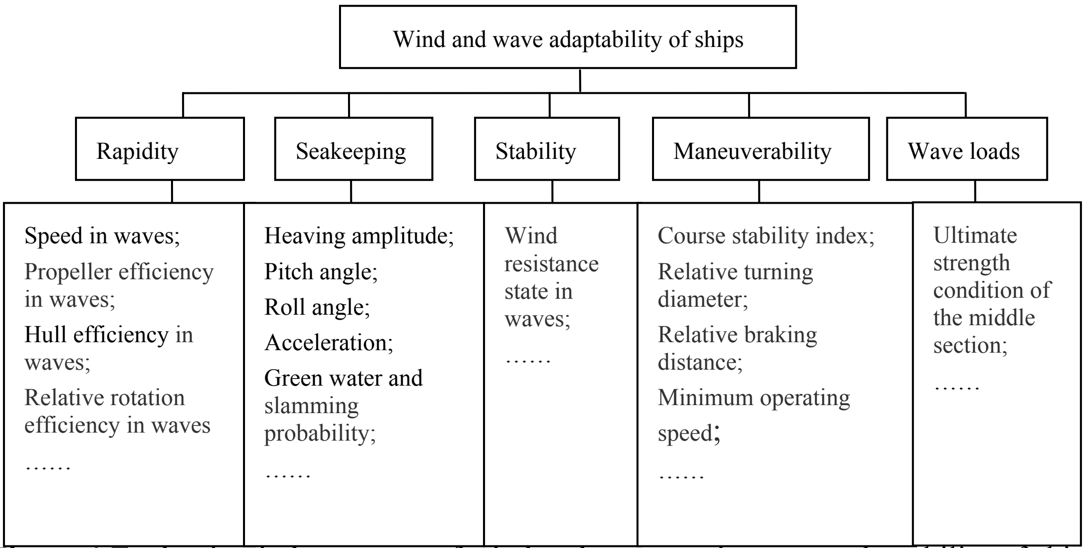

Figure 1 Evaluation index system of wind and wave environment adaptability of ships

2.2 Evaluation index metric analysis

Firstly, all indices are to be classified: the first type of indices are those with specific provisions in the specification, making direct influences on the safety and application of the ships; the measuring of such indices must meet specification requirements; if the specification requirements are not met, the index value is 0. The second type of indices are those without definite requirements in the specification; the measuring of such indices can be evaluated according to the comparison between the actual value and the reference value; the index with good performance presents a higher score.

（1）Measurement index of rapidity

This paper uses the sailing speed in waves V_{sw} as the evaluation index in rapidity evaluation. According to the still water resistance test and the seakeeping performance test data in waves the sailing speed V_s in the still water at the same power is used for the reference to evaluate the rapidity of ships in the waves.

（2）Measurement index of seakeeping performance

This paper, based on the ship characteristics and the data analysis, proposes the seakeeping performance measurement indices to complete a certain task at six levels of sea conditions as follows:

Rolling angle amplitude $\varphi_a \le 16°$; Pitching angle amplitude $\theta_a \le 4.8°$; Heaving amplitude $Z_a \le 2$m; Vertical acceleration at bow $A_f \le 0.4$g; Slamming probability at the bow bottom $P_{slm} \le 0.03$; Green water frequency $X \le 0.5$times/min.

（3）Measurement index of stability

Since the current stability specification mainly focuses on the static stability and the stability of large dip angle, it is difficult to consider the influence of the waves on the dynamic stability. The wind and wave stability of ships in the specification only considers the effect of the wind. In this paper, according to the requirements of stability specification, the stability is evaluated for a particular ship based on its displacement and the wind resistance level U.

（4）Measurement index of wave loads

The limit strength conditions of ships given in the specification shall meet:

$$\frac{M_u}{M_s + M_w} \geq 2.6 \tag{3}$$

This paper uses the above formula as the measurement index to evaluate the wave loads index of ships.

（5）Measurement index of maneuverability

Concerning the evaluation of the ship maneuverability index, there is no internationally recognized measurement index for ship maneuverability in still water, and it is even more difficult to determine the maneuvering measurement index in waves. Since it is very difficult to measure the ship maneuverability in waves, this paper will not evaluate the maneuverability index in waves.

2.3 Construction of two layers of index weight judgment matrix

After the evaluation index system and each index measurement index are determined, the focus is on the relative importance degree of each evaluation index influencing the wind and wave environment adaptability of ships in order to determine the weight of each index. This paper, based on the two-layer evaluation index system built previously, establishes the judgment matrix of each evaluation index in layers, as shown in Tables 1 and 2.

Table 1 Judgment matrix of the first level evaluation index

Index	A_1	A_2	A_3	A_4	A_5
A_1	1	A_{12}	A_{13}	A_{14}	A_{15}
A_2	A_{21}	1	A_{23}	A_{24}	A_{25}
A_3	A_{31}	A_{32}	1	A_{34}	A_{35}
A_4	A_{41}	A_{42}	A_{43}	1	A_{45}
A_5	A_{51}	A_{52}	A_{53}	A_{54}	1

Where A_1 , A_2 , A_3 , A_4 , A_5 stand for the first level environment adaptability index such as seakeeping performance, rapidity, stability, wave loads, and maneuverability.

Table 2 Judgment matrix of the second level evaluation index

A_i	a_1	a_2	…	a_n
a_1	a_{11}	a_{12}	…	a_{1n}
a_2	a_{21}	a_{22}	…	a_{2n}
…	…	…		…
a_n	a_{n1}	a_{n2}	…	a_{nn}

Where n is the number of evaluation indices under the first level indices.

After the judgment matrix is determined, the largest characteristic vector of the judgment matrix can be calculated, namely, the weighting coefficient of the established evaluation index system.

3. Construction of comprehensive evaluation equation

According to the wind and wave environment adaptability evaluation index system constructed previously, a multi-objective comprehensive evaluation index of R_x is put forward. R_x is set as the wind and wave environment adaptability evaluation value under a certain direction and speed of ships. The value of R_x can be calculated as follows:

$$R_x = \sum_{i=1}^{n} K_i (-1)^j (1 - P_i / P_i') \begin{cases} j = 0 & \text{The smaller the response amplitude is, the better the adaptability is} \\ j = 1 & \text{The bigger the response amplitude is, the better the adaptability is} \end{cases} \tag{4}$$

where: P_i – the probability of occurrence of various responses in consideration of environment parameter of ships, or response value; P'_I – allowable probability of occurrence of various responses, or allowable response value; n – quantity of environment adaptability factors to be considered; K_i –weighting coefficient.

The comprehensive evaluation index established above is related to the actual response value of each index, the measurement index of each evaluation index, and the weighting coefficient of each evaluation index. After calculating the above parameters and inserting them into formula (4), the comprehensive quantitative assessment for the wind and wave environment adaptability of ships can be obtained.

4. Evaluation examples

In this paper a hybrid monohull NH1 and a round bilge monohull S0 with the same tonnage level are used as the evaluation objects. The constructed evaluation system is applied to evaluate the wind and wave environment adaptability of the ships, and to verify and analyze the established evaluation index system and evaluation method.

The wind and wave environment adaptability of the ships is evaluated for the sea states 5 and 6 (with significant wave height H1/3 = 3m, 5m) at a speed of 24 knots. The dimensions of the two considered ships are given in Table 3, and the drawing lines as shown in Figures 2 and 3.

Table 3 Main parameters of the two considered ships

Ships	L_{wl}/m	B_{wl}/m	T/m	Δ/t
NH1	125	14.2	4.5	3406.8
S0	125	13.8	4.05	3446.6

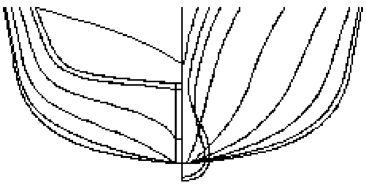

Figure 2 Sections of round bilge ship S0

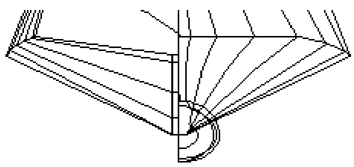

Figure 3 Sections of hybrid monohull NH1

4.1 Actual response calculations of underlying index

The response amplitude of the indices can be obtained in two ways, including the model test and theoretical calculation. For the indices where the test data are available, the test data are used in principle as the actual response value of a particular index; for those indices without available test data, the commonly used theoretical methods are adopted for calculation. The calculation result is used as the actual response value of a particular index. The specific calculation result will be given in the later section.

4.2 Calculation of weight judgment matrix in two layers of index

By solving the weight judgment matrix of each index, the characteristic vector of the evaluation index system is calculated, and the weight of each evaluation index is determined. According to the relative importance degree of various performances, the 1, 3, 5, 7 and 9 scale method is used to quantize the comparison of any two elements. The first level of index weight judgment matrix established in this paper is shown in Table 4:

Table 4 Judgment matrix of weighting coefficients

A	A_1	A_2	A_3	A_4
A_1	1	1/3	1/5	1
A_2	3	1	1/2	3
A_3	5	2	1	5
A_4	1	1/3	1/5	1

where, A_1 – stability，A_2 – rapidity，A_3 – seakeeping performance，A_4 – wave loads.

The characteristic value, λ=4.004, characteristic vector, W= (0.0989, 0.2839, 0.5183, 0.0989. By calculation, the random consistence ratio CR=0.00156 < 0.10, meeting the consistence requirements.

The weight judgment matrix of each second level of index is calculated as below:

Firstly, the weight judgment matrix of seakeeping performance index is calculated. The constructed weight judgment matrix is shown in Table 5:

Table 5 Judgment matrix of weighting coefficients for seakeeping performance index

A_3	u_1	u_2	u_3	u_4	u_5	u_6
u_1	1	1/3	1	2	3	5
u_2	3	1	3	2	5	6
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	1/3	1	2
u_6	1/5	1/6	1/5	1/5	1/2	1

where, u_1 – pitching，u_2 – rolling，u_3 – heaving，u_4 – bow vertical acceleration，u_5 – slamming probability，u_6 – green water frequency.

The characteristic value, λ= 6.208479, characteristic vector, W= (0.0187, 0.0373, 0.0187, 0.0144, 0.0062, 0.0038), the random consistence ratio CR=0.03322 < 0.10, meeting the consistence requirements.

Similarly, the rapidity of various index weights in waves is obtained:

Where, the characteristic value, λ= 4, characteristic vector, W= (0.1774, 0.0355, 0.0355, 0.0355), the random consistence ratio CR=0 < 0.10, meeting the consistence requirements. Where, w_1 – sailing speed in waves, w_2 – open propeller efficiency, w_3 – hull efficiency, w_4 – relative rotation efficiency.

The characteristic vector for comprehensive evaluation of the wind and wave environment adaptability evaluation index system can be solved by formula (5):

$$K = W_i \cdot u_j \tag{5}$$

where, K – comprehensive judgment characteristic vector, W_i – single sailing performance weighting coefficient, u_j – weighting coefficient of each evaluation index under the level of its sailing performance.

The stability evaluation index in waves only chooses the wind resistance level, and the wave loads evaluation index only applies condition of ultimate bending moment, so the respective characteristic vectors of these two indices are both 1. For the evaluation of the wind and wave environment adaptability of ships, provided all evaluation indices of the response amplitude can not be given, these evaluation indices should be rejected, and the normalization processing for the weight coefficient of other indices shall be done.

4.3 Evaluation analysis for wind and wave environment adaptability of the two ships

This paper uses the analytic hierarchy process and fuzzy comprehensive assessment method to make wind and wave environment adaptability assessment for a 4000-tonnage high seakeeping performance monomer hybrid monohull NH1 and a round bilge S0 having the same tonnage. The evaluation results of the two methods are given below.

(1) Evaluation based on analytic hierarchy process

Substituting the response amplitude, the measurement index and weighting coefficient of each index into the comprehensive evaluation index of wind and wave environment adaptability, the wind and wave environment adaptability of the two considered ships in sea states 5 (H1/3=3m) and 6 (H1/3=5m) are calculated (Tables 6 and 7).

Table 6 Evaluation results for the two ships in sea state 5

Index	Weighting coefficient	Measurement value	Actual response value	
			NH1	S0
θ/ °	0.018664	≤4.8	1.02	1.20
Z/ m	0.018664	≤2	0.60	0.56
A_f / m/s	0.014348	≤3.92	1.91	2.61
X/ Times/min	0.003772	≤0.5	0.347	0
V_{sw}/ kn	0.177407	24	23.04	22.55
U/ m/s	0.518287	≥52	185.94	143.14
m	0.098931	≥2.6	4.4	3.6
$R_x = \sum_{i=1}^{n} K_i(-1)^j(1-P_i/P_i^{'})$			1.433	0.972

Table 7 Evaluation results for the two ships in sea state 6

Index	Weighting coefficient	Measurement value	Actual response value	
			NH1	S0
θ/ °	0.01867	≤4.8	1.45	2.13
Z/ m	0.01867	≤2	0.96	0.92
A_f / m/s	0.0143	≤3.92	2.35	4.77
X/ Times/min	0.0038	≤0.5	0.074	0.265
V_{sw}/ kn	0.1774	24	22.81	22.27
U/ m/s	0.5183	≥52	185.94	143.14
m	0.0989	≥2.6	4.4	3.6
$R_x = \sum_{i=1}^{n} K_i(-1)^j(1-P_i/P_i^{'})$			1.426	0.953

As can be seen from the evaluation results for wind and wave environment adaptability of the two considered ships, the wind and wave environment adaptability of the hybrid monohull is better than that of the round bilge hull, and the evaluation results for the two sea state conditions are very close, indicating that the wind and wave environment adaptability of the NH1 is better than that of the S0 under medium sea state conditions.

In order to truly reflect the relative importance of every index, the analytic hierarchy process combining with 100 score grading system is introduced in this paper. This system makes score for each index according to the actual response amplitude of every index. The scoring criteria are shown in Table 8.

Table 8 Grading standard of each index

Indices	Conditions	Grading scores
θ / °	$\theta > 4.8$	0
	$1 \leq \theta \leq 4.8$	$100*(4.8-\theta)/3.8$
	$\theta < 1$	100
Z/ m	$Z > 2$	0
	$0.5 \leq Z \leq 2$	$100*(2-Z)/1.5$
	$Z < 0.5$	100
A_f / m/s^2	$A_f > 3.92$	0
	$1.2 \leq A_f \leq 3.92$	$100*(3.92- A_f)/2.72$
	$A_f < 1.2$	100
X / times/min	$X > 0.5$	0
	$0.1 \leq X \leq 0.5$	$100*(0.5-X)/0.4$
	$X < 0.1$	100
V_{sw} / m/s	$V_s < 16$	0
	$16 \leq V_{sw} \leq 23$	$100*(V_{sw}-16)/7$
	$23 < V_s \leq 24$	100
U / m/s	$U < 52$	0
	$52 \leq U \leq 150$	$100*(U-52)/98$
	$U > 150$	100
$m = \frac{M}{M_s +}$	$m < 2.6$	0
	$2.6 \leq m \leq 5.0$	$100*(m-2.6)/2.4$
	$m > 5.0$	100

The evaluation of each index weight and evaluation equation uses the same way as previously described. The evaluation results are shown in Tables 9 and 10.

Table 9 Evaluation results for the two ships in sea state 5 in grading system

Indices	Weighting coefficients	Consistence values	NH1		S0	
			Response values	Scores	Response values	Scores
θ	0.0187	0.146	1.02	99.5	1.20	94.7
Z	0.0187	0.146	0.60	93.3	0.56	96
A_f	0.0143	0.116	1.91	73.9	2.61	48.2
X	0.0038	0.03	0.347	38.3	0	100
V_{sw}	0.1774	0.2656	23.04	52	22.55	27.5
U	0.5182	0.1482	185.94	100	143.14	93
m	0.0989	0.1482	4.4	75	3.6	41.7
Evaluation values			86.2		72.74	

Table 10. Evaluation results for the two ships in sea state 6 in grading system

Indices	Weighting coefficients	Consistence values	NH1		S0	
			Response values	Scores	Response values	Scores
θ	0.0187	0.1460	1.450	88.2	2.130	70.3
Z	0.0187	0.1460	0.960	69.3	0.920	72.0
A_f	0.0143	0.1160	2.350	57.7	4.770	0.0
X	0.0038	0.0301	0.074	100.0	0.265	58.8
V_{sw}	0.1774	0.2656	22.810	40.5	22.270	13.5
U	0.5183	0.1482	185.940	100.0	143.140	93.0
m	0.0989	0.1482	4.4	75.0	3.600	41.7
Evaluation values			83.0		67.8	

This paper only uses the analytic hierarchy process and combines the 100 score grading analytic hierarchy process to make the wind and wave environment adaptability assessment for the hybrid monohull NH1w and the round bilge hull S0 at a speed of 24 knots in sea states 5 and 6. The results are shown in Figures 4 and 5.

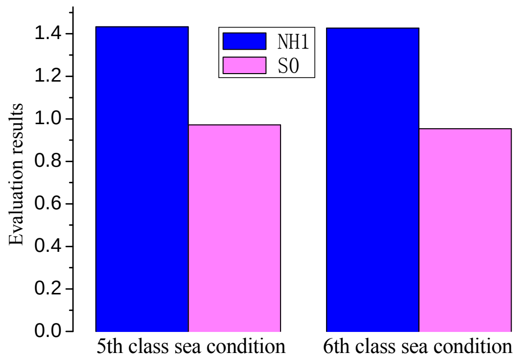

Figure 4 Evaluation results of AHP method

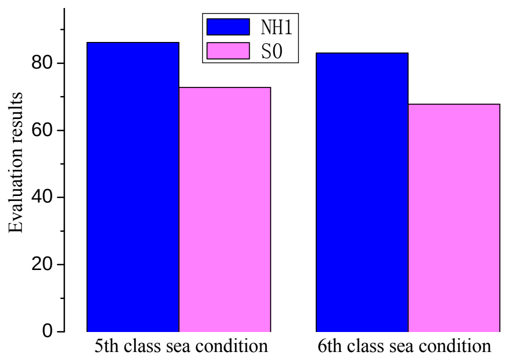

Figure 5 Evaluation results of AHP method combined 100 grading

The above evaluation results show that the difference of comprehensive evaluation index value by combining the 100 score grading system is greatly reduced compared with that of only using the analytic hierarchy process, indicating that the selection of weight and the measurement method of each index will have much impact on the assessment results.

(2) Evaluation based on the fuzzy comprehensive assessment method

In order to reduce the influence of man-made factors on the results of evaluation, based on the theory of fuzzy mathematics, this paper establishes the second level of fuzzy comprehensive assessment model for each evaluation index. The specific evaluation process and steps are as follows:

Firstly, establish the factor set.

For the sake of simplicity, this paper selects some typical representative indices. The scope of environment adaptability includes rapidity, seakeeping performance, stability and wave loads. Each scope includes several sub-factors.

The first level factor set $U=\{u_1, u_2, u_3, u_4\}$, where, u_1 – seakeeping performance, u_2 – rapidity , u_3 – stability , u_4 – wave loads.

The second level factor set $u_1=\{ u_{11}, u_{12}, u_{13}, u_{14}\}$, where, u_{11} – significant amplitude of pitching , u_{12} – significant amplitude of heaving , u_{13} – significant amplitude of bow vertical acceleration , u_{14} – green water frequency.

$U_2=\{u_{21}, u_{22}, u_{23}, u_{24}\}$, where, u_{21} – speed in waves , u_{22} – propeller efficiency , u_{23} – hull efficiency , u_{24} – relative rotating efficiency.

Secondly, establish a weight set.

In order to facilitate the analysis, this paper still uses the weight of each evaluation index obtained in the previous judgment matrix.

Thirdly, establish an alternative set.

For concise clarity of scoring, 100 score grading system is given, $V = \{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100\}$, 11 grades in total. All indices use this alternative set.

Finally, make the fuzzy evaluation.

For various factors influencing the environment adaptability, the smaller the significant pitch, the significant heave, the vertical acceleration of ship stem, and the deck wave frequency value, the better the environment adaptability of ships. However, the bigger the sailing speed in the waves, the propeller open water efficiency, the hull efficiency, the relative rotation efficiency, the wind resistance and the safety coefficient, the better the environment adaptability of ships. According to the above information, a certain parameter value can be scored respectively. In line with the usual evaluation thought process of human beings, a ridge type function is used.

$$N = 50[1 + (-1)^k \sin\frac{\pi}{u_{\max} - u_{\min}}(u - \frac{u_{\max} + u_{\min}}{2})]$$

$$\begin{cases} k = 0 \text{The value is bigger, the adaptability is better.} \\ k = 1 \text{The value is smaller, the adaptability is better.} \end{cases} \quad (6)$$

Where, N – grading scores, u_{max} – maximum value; u_{min} – minimum value; u – actual value.

Determine each index score result according to the above subordinating function, as shown in Table 11.

Table 11 Scores of each index

First level	Second level	H1	0
Seakeeping performance	θ	9.1	8.8
	Z	3.1	6.3
	A_f	4.6	0.4
	X	4.7	5.3
Rapidity	V_{sw}	4.6	9.9
Stability	U	6.3	9.8
Wave loads	m	5.0	0.2

The subordinating function of index score N related to each alternative element is established in this study. The fuzzy distribution in the normal distribution form is used to calculate the score of a certain index to get the subordinating function in each score level in the alternative set:

$$r(v_k) = e^{-0.005(v_k - N)^2} \quad (7)$$

where: $r(x)$ – subordinating function; v_k – element grading level in alternative set; N – the score of this index.

This paper uses the $M(\bullet,+)$ algorithm, i.e. $b_{ik} = \sum_{j=1}^{m} a_{ij} r_{ijk}$. The result of the first level of fuzzy comprehensive assessment is as follows,

$$B_1 = A_1 \circ R_1 = \{0\ \ 0.003\ \ 0.035\ \ 0.097\ \ 0.129\ \ 0.127\ \ 0.099\ \ 0.096\ \ 0.142\ \ 0.159\ \ 0.112\}$$

It can be also obtained like this,

$$B_2 = A_2 \circ R_2 = \{0\ \ 0\ \ 0\ \ 0.007\ \ 0.038\ \ 0.085\ \ 0.099\ \ 0.095\ \ 0.148\ \ 0.275\ \ 0.252\}$$

$$B_3 = \{0\ \ 0\ \ 0\ \ 0.013\ \ 0.106\ \ 0.327\ \ 0.373\ \ 0.156\ \ 0.024\ \ 0.001\ \ 0\}$$

$$B_4 = \{0.018\ \ 0.130\ \ 0.352\ \ 0.352\ \ 0.130\ \ 0.018\ \ 0.001\ \ 0\ \ 0\ \ 0\ \ 0\}$$

The second level fuzzy comprehensive evaluation result is as follows,

$$B = A \circ R = A \circ \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \{0.002\ \ 0.018\ \ 0.055\ \ 0.076\ \ 0.08\ 0.108\ \ 0.110\ \ 0.088\ \ 0.116\ \ 0.185\ \ 0.161\}$$

Use the weighted average method, $F = V \cdot B^T$ to get the score of the compound ship, 66.95; similarly, the score of the round bilge hull, 50.5, can be obtained.

The evaluation results for analytic hierarchy process combining with the 100 score grading method and fuzzy comprehensive assessment method are shown in Table 12. The evaluation results comparison between the two methods is shown in Figure 6.

Table 12 Evaluation results of the two methods

Evaluation method	NH1	S0
AHP	83.0	67.8
FCA	66.95	50.5

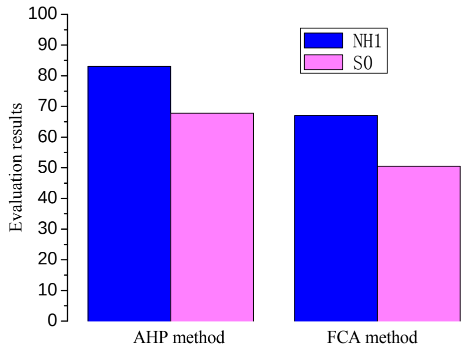

Figure 6. Evaluation results of the two methods

As can be seen from the results above, the evaluation results for the two considered ships by using the analytic hierarchy process combining with 100 score grading method and the fuzzy comprehensive assessment method do not show much difference. However, the value of the fuzzy comprehensive assessment method is smaller. Thus, the selection of the evaluation method also has a great influence on the evaluation results. The analysis of the two different evaluation methods shows that the subordinating function applied in the fuzzy comprehensive assessment method has great influence on the evaluation results.

4.4 Influence analysis of index weight judgment matrix changes on evaluation results

During the process of wind and wave environment adaptability assessment for the two considered ships, each index weight judgment matrix is chosen by manual intervention method. However, this matrix will affect the results of the evaluation. To study the influence degree of the weight judgment matrix of evaluation index on the evaluation results, this paper, by using two levels of judgment matrices in different forms, calculates the evaluation result respectively, constructs four different judgment matrices and calculates the evaluation results, so as to analyze the influences of changes for the index weight judgment matrix on the results of evaluation. The change plan for four kinds of the judgment matrices is shown in Table 13.

Table 13 Four plans of different judgment matrices

Plans	Content
Plan 1	The same as the above plan
Plan 2	The importance of each index is equal
Plan 3	The importance of the first level indices is opposite to plan 1
Plan 4	The importance of the two levels indices is opposite to plan 1

According to plan 2, establish the judgment matrix in each level and substitute it into the comprehensive evaluation index formula to get the wind and wave environment adaptability evaluation results for the two considered ships. The 100 score grading evaluation result for four kinds of judgment matrices for sea state 6 is shown in Table 14. The comparison of evaluation results is shown in Figure 7.

Table 14 Evaluation results for four kinds of judgment matrices

Matrix plan	NH1	S0
Plan 1	83.0	67.8
Plan 2	81.5	58.9
Plan 3	73.5	46.5
Plan 4	81.9	50.4

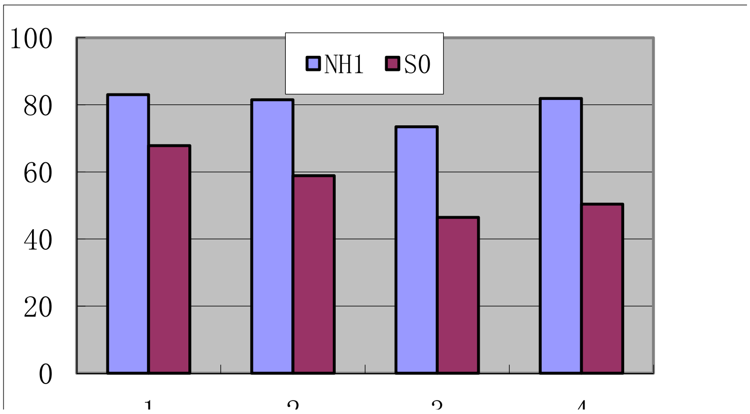

Figure 7 Evaluation results for four kinds of judgment matrices

It can be seen from the evaluation results for all four kinds of judgment matrices in Table 14 and Figure 7 that the selection of judgment matrix can make great influence on the final evaluation result. In the evaluation index system for the wind and wave environment adaptability of ships, whether each index weight coefficient is determined reasonably or not directly affects the scientificity of the evaluation result. Therefore, determining the weight coefficient is both the difficulty of application of the evaluation method and the key point of ensuring the scientific and reasonable evaluation result.

5. Conclusions

Based on the evaluation results of each judgment matrix, the following conclusion can be made:

(1) The results of using different evaluation methods of wind and wave environment adaptability for two different types of ships show that the adaptability of the hybrid monohull NH1 is better than that of a round bilge monohull S0 where the fuzzy index attribute has a great influence on the evaluation results.

(2) By using different evaluation models and judgment matrices to evaluate the wind and wave environment adaptability of the two considered ships, the significant difference in the evaluation results was found, indicating that the selection of evaluation model and evaluation index weight will produce great influence on the evaluation results.

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