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Combined Annoyance Assessment of Ship Structural Vibration and Ambient Noise

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Abstract: Background: Noise and vibration are environmental pollutants that endanger people's productivity and sleep quality in ships, but the coupled effect in ship cabins has not been studied. This study aimed to assess the coupled effect of noise and vibration in ship cabins and propose a comfortable range of noise and vibration. Methods: Three different accommodation cabins were chosen to measure noise and vibration levels and investigate their satisfaction. A revised model combining exponential membership functions was proposed to reveal the relationship between noise and vibration level and its response. The annoyance rate from greater to lesser was classified as A, B, C, D, and E. Results: All measurement levels were satisfied with the acceptance ranges of standards. While subjects felt high annoyance in the crew lounge, subjects in passenger and dining cabins felt slightly annoyed. Conclusions: By combining measurements and subjective investigations, the prediction performance of the revised annoyance model was verified. The noise level reached 57.5 dB(A), and the acoustic condition had a greater impact on subjective feelings than the vibration level. For grade E demands, the vibration level should be lower than 0.095 m/s^2, and the noise level should be less than 54 dB(A).

Keywords: ship cabin; vibration and noise; annoyance rate model; combined annoyance rate

Citation: Liu, H.; Lin, X.; Gong, Z.; Shi, J. Combined Annoyance Assessment of Ship Structural Vibration and Ambient Noise. *Buildings* **2023**, *13*, 363. https://doi.org/10.3390/buildings13020363

Academic Editors: Wei Liu, Manuel Carlos Gameiro da Silva and Dayi Lai

Received: 20 December 2022
Revised: 19 January 2023
Accepted: 26 January 2023
Published: 28 January 2023

1. Introduction

Ship cabins are places for passengers and crew to rest, work, dine and entertain. A high level of noise may cause headache and difficulties in communication [1]. Vibration may increase the risk of accidents [2]. Therefore, noise and vibration need to be evaluated in the cabin environment to achieve high productivity and high-quality sleeping for subjects.

Noise, as a detectable environmental factor, is gradually gaining attention. Numerous studies on noise influence have been conducted. Borelli D et al. [3] conducted ship noise experiments under transient and steady conditions and concluded the influence of ship speed, operation condition and ventilation system on the noise level. Kurt RE et al. [4] investigated the noise exposure level in a ship to evaluate its influence on crew members and proposed a series of noise level standards in dB(A). IMO-2012 [5] adopted limits in terms of dB(A) values to assess the level of comfort onboard. Although the international guidelines only provide indications relating to the A-weighted sound pressure level and the acoustic insulation requirements of ship cabins, Borelli D. et al. [6], Badino A. et al. [7] and Rocca M. et al. [8] highlight the importance of having suitable acoustic indicators derived from those typically used in buildings or specifically designed for boats interiors.

Vibration is also an essential factor in assessing a subject's comfort, and vibration comfort is measured based on ISO 2631 [9] and BSI 6841 [10]. The full-frequency-weighted r.m.s accelerations (a_w) are generally regarded as universally applicable indicators for vibration. The responses of the human body to vibration are highly dependent on the frequency of vibration; therefore, frequency weighting is applied during the evaluation. The value of vibration acceleration beyond the most sensitive frequency range of the human body is frequency weighted and the equivalently converted to the vibration acceleration in the most sensitive frequency range. Omer H and Bekker A [11] found that vibration strongly affects subjects' sleep continuity and work activity. Liu HM et al. [12] investigated onboard vibration and noise comfort, indicating that onboard vibration levels are acceptable and noise levels are annoying to some subjects. Studies in other fields show that vibration and noise are always accompanied by each other, and it is essential to consider the effects of both noise and vibration simultaneously [13–15].

The combined effects of noise and vibration on the human body have been studied, but as far as which is the main factor, and their detailed effects, depends on the actual situation. Huang Y and Li D [16] noted that vibration-induced discomfort does not equidistantly increase with root mean square (r.m.s) acceleration, and noise is predominant in automotive systems. Noise also plays a significant role in occupant health in the flight cabin [17]. At a certain level, the noise will make the "masking effect" on overall discomfort, which means noise will inhibit the discomfort feeling caused by vibration [18]. Moreover, Ögren M et al. [19] found that the impact of vibration on noise comfort was more significant than the impact of noise on vibration comfort.

Physiological and psychological factors are also important factors in evaluating subjects' comfort [20,21]. There are differences in occupants' responses under the same stimuli, and their degree of perception under different stimuli is much less explored. The "annoyance rate" was proposed to describe the proportion of occupants who developed annoying feelings under certain external physical stimuli, and it can be used to evaluate the influence of vibration and noise. Multiple methods were adopted to evaluate the effects of noise and vibration. Griffin MJ and Whitham EM [22] found that individual sensitivity to external stimuli obeyed a normal and logarithmic normal distribution. Tao Z et al. [23] used a logarithmic normal function to assess the noise annoyance of subjects who lived in buildings around subways. Wang G et al. [24] adopted the logarithmic normal function to evaluate subjects' vibration comfort. The above functions used the annoyance rate to clarify the impacts of noise and vibration on the subject's comfort. The associations between noise level and subject comfort can be clarified by the annoyance rate, which has been successfully used in several studies [25,26]. Several experiments on combined noise and vibration have been conducted, and the calculation method for total annoyance rates was obtained, which will be used in the Theory section [13,14,27].

In this paper, a passenger cabin, a crew cabin and a dining cabin were selected to investigate the relationship between noise and vibration and the respondents' levels of satisfaction and to explore the relationship between noise level and the noise feeling of participants without considering the noise spectrum under the IMO standard. The noise level was measured in the equivalent continuous A-weighted noise pressure levels L_{Aeq} (dB(A)), and the vibration level was measured in full-frequency-weighted r.m.s acceleration a_w (m/s^2). In addition to noise and vibration, outdoors average temperature, airflow rate and relative humidity were also recorded. The results of the average temperature, airflow rate and relative humidity during the test period will be presented in the study design part. Through comparisons of membership functions based on previous research, a revised annoyance model was proposed. The combined annoyance rate index can be used to evaluate a respondent's annoyance under vibration and noise, which is beneficial for proposing the acceptance value of noise and vibration.

2. Materials and Methods

2.1. Theory

This paper adopted the logarithmic annoyance function [24] to evaluate onboard subjective feelings under noise and vibration stimuli. Due to people have different feelings toward the external stimuli x, the feeling under the stimulus of levels u was calculated to represent the majority of subjects' feelings through the annoyance rate model.

$$A(x) = \int_{u_{\min}}^{\infty} f(x|u) \cdot v(u) du = \begin{cases} 0 & u < u_{\min} \\ \int_{u_{\min}}^{\infty} \frac{1}{u\sigma\sqrt{2\pi}} \exp\left[\frac{-(\ln(u/x + 0.5\sigma^2)^2}{2\sigma^2}\right] \cdot v(u) du & u_{\min} < u < u_{\max} \\ 1 & u > u_{\max} \end{cases} \tag{1}$$

where $f(x \mid u)$ is the expression of the sensitivity differences, u is the vibration level or noise level and $v(u)$ is the membership function, which is a mapping from u to a space from zero to one.

The membership function expresses the influence of u on the annoyance rate. If u is below the lower limit, the annoyance rate should be zero; if u equals or exceeds the upper limit, the annoyance rate will be one. The annoyance rate can be much easier to show through the membership value. Considering the ship's environment, the membership function needed discussion. According to Weber-Fechner law, the original membership function divided subjects' responses into multiple equal sense distance intervals, while subjects' feelings about vibration and noise are nonisometric [28]. The exponential formation is capable of measuring the nonisometric relationship, which applied to the original membership function is shown in Equation (2):

$$vi = \left(\frac{i-1}{K-1}\right)^m, i = 1, 2, 3, \ldots, K \tag{2}$$

where m is a constant representing the relationship between perception and stimulus.

Tu et al. [29,30] defined the membership degrees of vibration responses as 0, 0.3, 0.6, 0.8 and 1. Wang et al. [31] defined the membership degrees of noise responses as 0, 0.4, 0.7 and 1. From the vibration experiments of Tu, m can be obtained as 0.805 ± 0.031; from the noise experiments of Wang et al., m equals 0.848 ± 0.012. The final m took the value of 0.827 by averaging two indices to match vibration and noise.

Figure 1 shows that Equation (2) is closer to the experimental results than the non-exponential function, and Equation (2) with m = 0.827 can be used to calculate discrete points in continuous membership functions. The continuous membership function is calculated considering psychoacoustic factors, which is shown in Equation (3):

$$v(u) = k(u - u_0)^n \tag{3}$$

where k and n are constant coefficients, and u_0 is the lower limit of stimuli.

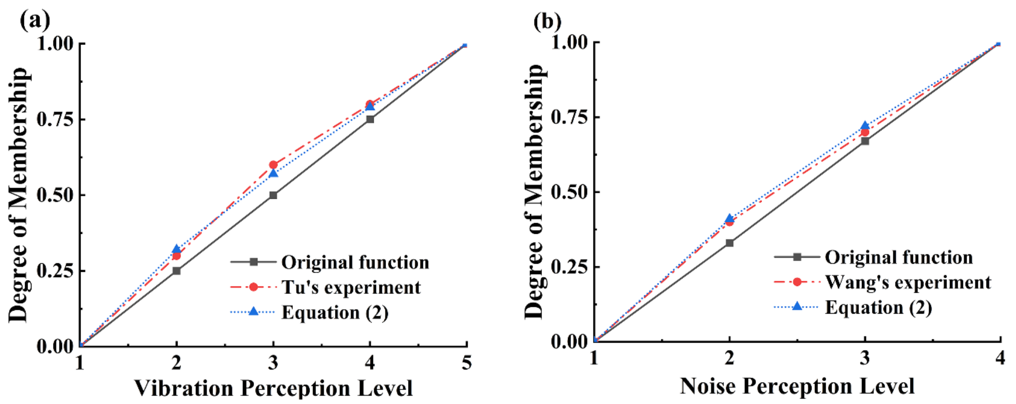

Figure 1. Comparisons of the original membership function, Equation (2), and the experimental results of vibration and noise: (**a**) comparing functions with Tu's experiment about vibration; (**b**) comparing functions with Wang's experiment about noise. (Two pictures were drawn according to Tu and Wang's perception experiment results).

According to the classification scheme of vibration [32] and noise [33], the membership degrees of the three points can be obtained as 0, 0.566 and 1. Three points of vibration from the standard [32] are r_1 = 0.0715 m/s^2 r.m.s, $2r_1$ = 0.143 m/s^2 r.m.s, and $4r_1$ = 0.286 m/s^2 r.m.s, which are substituted into Equation (3) as the following:

$$\begin{cases} k(r_1 - u_0)^n = 0 \\ k(2r_1 - u_0)^n = 0.566 \\ k(4r_1 - u_0)^n = 1 \end{cases} \tag{4}$$

Solving the above equation, the coefficients were obtained as k = 2.22, u_0 = 0.0715 and n = 0.518. The onboard annoyance rate considering vibration can be obtained in Equation (5).

$$A_1(x) = \begin{cases} 0 & r < r_{\min} \\ \int_{r_{\min}}^{\infty} \frac{1}{r\sigma\sqrt{2\pi}} \exp\left[\frac{-(\ln(r/x + 0.5\sigma^2)^2}{2\sigma^2}\right] \cdot 2.22(r - 0.0715)^{0.518} dr & r_{\min} < r < r_{\max} \\ 1 & r > r_{\max} \end{cases} \tag{5}$$

Three points of noise from the standard [33] are z_1 = 55 dB(A), z_2 = 65 dB(A), and z_3 = 75 dB(A), which are substituted into Equation (3) as the following:

$$\begin{cases} k(r_1 - u_0)^n = 0 \\ k(2r_1 - u_0)^n = 0.566 \\ k(4r_1 - u_0)^n = 1 \end{cases} \tag{6}$$

For the noise membership function, k = 0.085, u_0 = 55 and n = 0.821. The onboard annoyance rate considering noise is derived as Equation (7). The feeling evaluation of noise and vibration was described and quantified at the level of psychophysics and psychology after considering the ambiguity of subjective judgment criteria and the difference in perception ability under vibration and noise stimulation.

$$A_2(y) = \begin{cases} 0 & z < z_{\min} \\ \int_{z_{\min}}^{\infty} \frac{1}{z\sigma\sqrt{2\pi}} \exp\left[\frac{-(\ln(z/x + 0.5\sigma^2)^2}{2\sigma^2}\right] \cdot 0.085(z - 55)^{0.821} dz & z_{\min} < z < z_{\max} \\ 1 & z > z_{\max} \end{cases} \tag{7}$$

Because passengers cannot rate the vibration or noise alone in the field study, the combined effect of vibration and noise will be calculated by models as follows.

Paulsen R and Kastka J [13] assumed that the total annoyance is a summation of the single annoyance, and the annoyance rate varied from 0 to 9. The regression equation is as follows.

$$S = 6.29 + 4.61\log_{10}(v_m) + 0.003L_{eq} \tag{8}$$

Lee PJ and Griffin MJ [14] adopted the dominance model and the independent model to predict the total annoyance caused by noise and vibration, and the annoyance rate varied from 0 to 10. The regression equations for the dominance model and the independent model are as follows.

$$S = 0.733A_D + 1.147 \tag{9}$$

where A_D means that the annoyance rate of vibration or noise is much greater than another.

$$S = 0.48A_1(x) + 0.64A_2(y) + 1.033 \tag{10}$$

where $A_1(x)$ and $A_2(y)$ are the annoyance rates for vibration and noise, respectively.

Ke S and Wei Z [27] proposed a root-mean-square equation to evaluate the combined effect of noise and vibration. The annoyance rate varied from 0 to 1, and if S exceeded one, then set S equals to one. The regression equation is as follows.

$$S = \sqrt{\alpha \cdot {A_1}^2(x) + \beta \cdot {A_2}^2(x)} \tag{11}$$

where S is the combined annoyance rate; $A_1(x)$ and $A_2(x)$ are the annoyance rates of structural vibration and ambient noise, respectively; and α and β are correction weights ranging from -1 to 1, which generally take a value of 1.

2.2. Method

2.2.1. Study Design and Procedure

The study was conducted in the "Baotuo ship", a short-haul luxury passenger ship that sailed through the East China Sea between the Shanghai City and Zhoushan areas of Zhejiang Province with a subtropical monsoon climate. The rated passenger capacity is 216, and there are eight service workers and ten crew members, including four pilots. A passenger cabin, a crew cabin, and a dining cabin were selected as study locations to cover all background subjects. Sixty subjects (34 males and 26 females) from all backgrounds were selected for the study after consultation with the head of the ship. The subjects' ages ranged from 18 to 66 years old, with an average of 32.7 years.

The investigation was conducted in the spring, while the average temperature was 24.2 °C, the relative humidity was 64.3%, and the airflow rate was 0.25 m/s. The thermal environment was comfortable for subjects. The beginning times were morning (8:30 to 12:30) and afternoon (13:00 to 18:00). The test was carried out after sailing for one hour to ensure the stability of data acquisition. The air conditioning system was turned off during the research period. Doors and windows were closed in the research area. Two study researchers measured and recorded environmental parameters, and one with management issued questionnaires to participants and offered an explanation of the questions. All participants were investigated for fifteen minutes in their seated position. The environmental parameters noise and vibration were measured during each questionnaire time, and the recording interval for each parameter was approximately fifteen minutes. The ABS [34] and IMO [5] give the measurement methods for vibration and noise in the ship cabin. The procedure was strictly carried out under specifications recommended by national standards.

The thermal environment was measured by the MI6401 indoor environment comfort tester. A class two calibrator (type awa6022a, China) and an IEPE sound pressure sensor (type INV9202, China) were used to calibrate and measure the sounds. The L_{Aeq} was calculated according to the procedure in BSI 2004 [35] and applying A-weighting to the one-third-octave band spectra measured by the IEPE INV9202 sound pressure sensor. An ICP triaxial accelerometer (INV9832A, for x-, y- and z-axes) was used to measure the vibrations, and the r.m.s vibration acceleration was obtained using ISO2631-2 (2003) [9]. The channels connected the vibration acceleration sensors in the x-, y- and z- directions in turn, and the sampling time in each direction was five minutes. The results of L_{Aeq} and r.m.s vibration acceleration were recorded in INV3080P dynamic balancing instruments. Detailed information on the devices is shown in Table 1.

Each research cabin set three measurement points: at the front (toward the head of the ship), middle and bow (toward the rear of the ship), and measurement points were placed more than 0.5 m from any boundary surface in the test cabin. The measurement height was set at a height of 1.1 m to measure the environmental parameters around seated subjects. A measuring time of five minutes was used, and this instrument integrated the recorded noise level into A-weighting as output values. The cabin's sound noise was obtained by averaging three positions' noise levels. The vibration levels were automatically processed by INV3080P into a full-frequency-weighted r.m.s value.

Table 1. Instrument-related parameters.

Instrument	Item	Range	Accuracy
MI6401	Air Temperature	5~40 °C	±0.2 °C
	Airflow Rate	0.05~1 m/s	±0.05 m/s
	Relative Humidity	0~100%	±3%
INV3080P	Vibration	0~20 m/s^2 (1~80 Hz)	3×10^{-6} m/s^2
	Noise	20~146 dB(A) (20~20,000 Hz)	±2 dB(A)

2.2.2. Questionnaire Design for the Annoyance Rate

A questionnaire was designed by the authors to collect data about structural vibration and ambient noise influences on subjects' annoyance rates in the accommodation areas of ships (see Appendix A). The questionnaire was administered on paper and designed in Chinese. All the subjects in this study completed questionnaires after staying in the cabin for more than 30 min. The questionnaire contained 17 items. Basic information (age, sex and identity) was recorded in the first part of the questionnaire. The respondents' perceptions of the noise level and vibration level were assessed by the following screening question: "Do you feel discomfort caused by vibration or shake? Do you think the vibration source was from hull shaking, machine vibrating and people walking?" "Do you feel discomfort caused by acoustics? Do you think the noise source was from waves slamming, machine noise, people walking, chatting and so on?" The choices were no and yes. Participants who answered yes to both questions were asked to participate in the follow-up survey.

In the next part, the combined effects of noise and vibration on respondents' annoyances were evaluated. Those were assessed by a series of questions: "How much were you annoyed for this reason" (six items: hull shaking, machine vibration and noise, wave slamming, chatting, people walking and others). Responses to these items were based on an eleven-point numerical scale (from 0 = not at all to 10 = extremely annoying) [36]. The "unnoticed" item was added to ensure that all feelings could be expressed. An eleven-point questionnaire is beneficial for subjects to fully express their actual feelings, and the voting results are transformed into a five-point scale to calculate the annoyance rate. The eleven-point scale was classified into five grades (E = [0, 0.2), D = [0.2, 0.4), C = [0.4, 0.6), B = [0.6, 0.8), A = [0.8, 1.0)), and a lower value indicated a lower annoyance rate. Paulsen R and Kastka J [13] found that subjects were more annoyed when they were surveyed about the overall situation than when they were asked for noise directly. All perceptible sources causing noise and vibration were listed in the questionnaire to avoid biased perception, which avoided a situation with some subjects only being sensitive to a certain range of stimuli, or people becoming more annoyed after being asked [37].

3. Results

3.1. Profile of the Sample

In this study, 200 questionnaires were distributed, 175 were returned, and, after excluding those who selected "do not feel vibration or noise" in the screening parts and those who completed it incompletely or randomly, 118 questionnaires were valid, providing a 59% response rate. To ensure the reliability and validity of surveys, the chosen subjects covered different genders, ages, backgrounds and characteristic information of the subjects of the sample is also listed in Table 2. The percentages of male and female subjects were 56.7% and 43.3%, respectively, and subjects younger than 40 years old accounted for 83.3% of the total number. In addition, the percentages of passengers and crew members were 78.3% and 13.3%, respectively.

Table 2. Characteristics information of the subjects.

Category	Male	Female
Age		
≤19	1	2
20–30	16	13
31–40	11	7
41–50	4	3
≥50	2	1
Identity		
Passenger	25	22
Crew members	8	0
Service workers	1	4

3.2. Vibration and Noise Measurement

The measured r.m.s vibration acceleration a_w values are shown in Figure 2. The upper limit of light vibration (LV) and the lower limit of severe vibration (SV) represent the minimum and maximum values that subjects felt acceptable, and values between upper and lower limitations belong to the acceptable range [32]. The LV in the passenger cabin and dining cabin is 0.0715 m/s^2 r.m.s, and the SV is 0.143 m/s^2 r.m.s. For the crew lounge, LV is 0.107 m/s^2 r.m.s, and SV is 0.214 m/s^2 r.m.s. Short lines note the maximum and minimum of the measured values, and the standard deviation (SD) of acceleration is expressed by the height of the box.

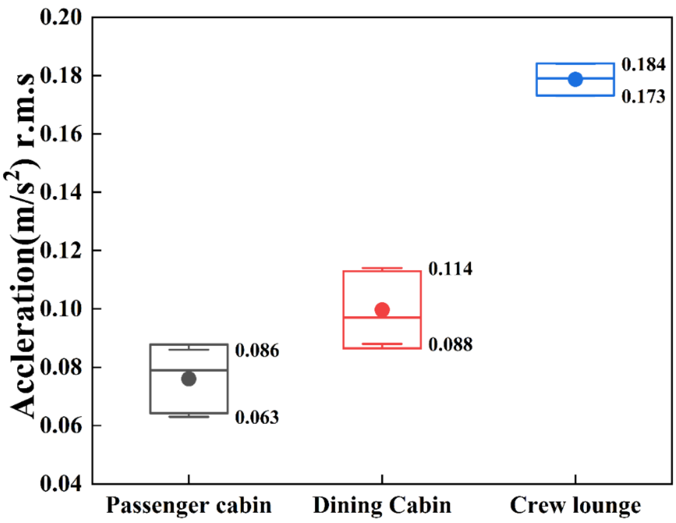

Figure 2. Distribution of vibration acceleration in three cabins.

The mean value, standard deviation and ratios are shown in Table 3, where the ratio to limitation was calculated by fitting the measured value to limit values. A ratio higher than 1 reflects measurement data greater than standards; otherwise, it indicates less than limitations. All vibration levels fell within acceptable ranges. The vibration levels in each cabin were stable according to low standard deviation (SD) values, which may be caused by stable sea conditions during the investigation. The increasing ratios follow, ordering from the passenger cabin and the dining cabin to the crew lounge, which means that vibration levels are closer to the severe vibration (SV) limit, and that subjects may feel more annoyed in this order.

Table 3. Statistical parameters of vibration for analysis in different measurement areas.

Area	Mean-a_w (m/s^2)	SD (m/s^2)	Ratio to LV	Ratio to SV
Passenger cabin	0.076	0.0096	0.881–1.203	0.441–0.601
Dining cabin	0.100	0.0108	1.231–1.594	0.615–0.797
Crew lounge	0.179	0.0045	1.617–1.720	0.808–0.860

Equivalent continuous A-weighted noise pressure levels (L_{Aeq}) are shown in Table 4, which presents an increasing trend from the passenger cabin to the crew lounge in ratios calculated by fitting the measured value to the maximum acceptable pressure level [5]. The modal behavior of rooms and plates may be the reason for the variation in noise and vibration in each cabin. The passenger cabin and dining cabin are located in the middle of the vertical direction, and the dining cabin is at the rear of the passenger cabin; in other words, it is at the stern of a ship. In the passenger cabin, the environment is relatively quiet, and the vibration and noise collection levels are relatively low. In the dining cabin, the test time was mealtime. Factors such as personnel walking and chatting, as well as the kitchen hood and other equipment, made the dining cabin environment noisy, but they were distracted by communication and meals. The lounge is located at the lower hold, adjacent to the air-conditioned and equipment rooms and bears the strongest vibration from the waves and the machine.

Table 4. A-weighted noise levels in different measurement areas.

Area	L_{Aeq}(dB(A))	Max Acceptable L_{Aeq} (dB(A))	Ratio to Max Acceptable Limit
Passenger cabin	49.1	55/60	0.8927/0.8183
Dining cabin	54.2	60/65	0.9033/0.8338
Crew lounge	57.6	60/65	0.9600/0.8862

3.3. Combined Annoyance Rate of Vibration and Noise

Figure 3 shows the distribution of respondents giving ratings in three cabins.

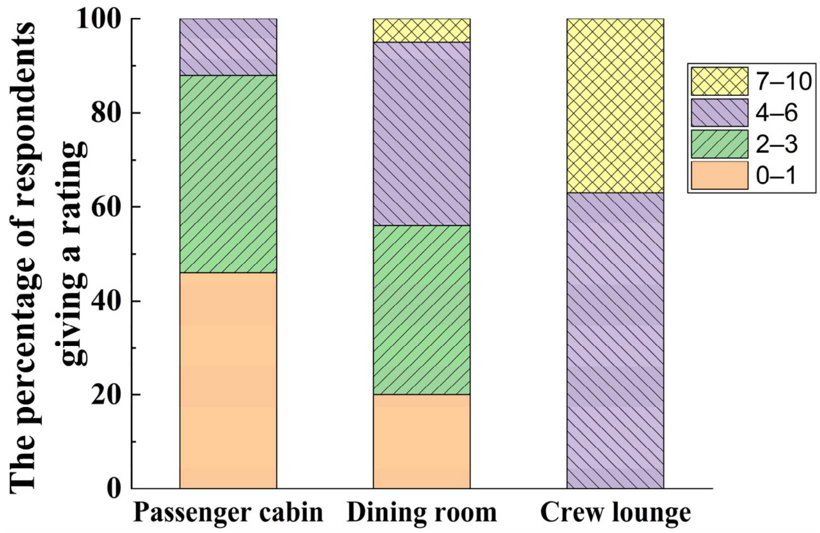

Figure 3. The distribution of respondents' ratings in three cabins.

According to the combined annoyance calculation methods, the annoyance rates of the three cabins were obtained, and the calculated annoyance rate results and mean annoyance rate results are presented in Table 5. Values of mean annoyance rates (MAR) indicated the mean level of respondents' annoyance votes obtained through Equation (12). Mean annoyance vote fall within the calculation results of the method of Ke S and Wei Z [27], which means that root-mean-square equation can predict the combined annoyance of vibration and noise in the ship's cabin well.

$$MAR = 0.1 \times v_1 + 0.3 \times v_2 + 0.5 \times v_3 + 0.8 \times v_4 \tag{12}$$

where v_1, v_2, v_3 and v_4 represent the number of respondents giving ratings in the ranges of 0–1, 2–3, 4–6 and 7–10, respectively, and coefficients in front of v_i are weights taken as the median values of annoyance rates.

Table 5. The statistics of the calculated combined annoyance rate and respondents' annoyance votes in three cabins.

Area	Calculation of Paulsen et al. [13]	Calculation of Lee et al. [14]	Calculation of Ke et al. [27]	Mean Annoyance Vote
passenger cabin	0.100–0.169(E)	0.108–0.124(E)	0.035–0.136(E)	0.232(D)
dining cabin	0.175–0.232(E-D)	0.126–0.132(E)	0.151–0.336(E-D)	0.363(D)
crew lounge	0.325–0.339(D)	0.160–0.162(E)	0.635–0.772(B)	0.611(B)

Where E- Not at all- [0, 0.2); D- Slightly annoyance- [0.2, 0.4); C- Moderately annoyance- [0.4, 0.6), B- Highly annoyance- [0.6, 0.8); A-Extremely annoyance- [0.8, 1.0).

The results through method of Ke S and Wei Z was selected as calculated annoyance rate in this paper. The mean annoyance rate in the passenger cabin is the lowest for its quiet environment. The mean annoyance rate is higher than its calculated annoyance rate, which might be caused by passengers' quiet expectations of the rest of the room. In the dining cabin, the mean annoyance rates meet the range of calculated annoyance rates. The communications among servers, crew members and passengers may distract the subject's attention, which causes people to be less susceptible to environmental vibration and noise. In the crew lounge, the mean annoyance rates meet the range of calculated annoyance rates, which has 63% of subjects voting moderate annoyance. It was learned from the conversation with crew members that those staff members felt mildly troubled because they got used to the current working environment, and the others who voted that they were highly uncomfortable said that the cabin's vibration and noise significantly impacted sleep health and psychology. In addition, the crew lounge was narrow, poorly ventilated and poorly illuminated.

3.4. Comparison between Noise Annoyance and Vibration Annoyance

Based on an in situ investigation in three ship cabins conducted during the spring, we analyzed the combined effects of noise and structural vibration on respondents' annoyances in the Baotuo ship. The prediction performance of the revised annoyance model was verified. The annoyance model results matched each cabin's respondents' annoyance votes, while the calculated annoyance rates in the passenger cabin were one degree smaller than the respondents' annoyance votes. The revised annoyance model will be used to discuss the recommended value of noise and vibration in the ship. According to the maximum acceptance range ISO 6954 [32], the vibration level was divided into nine parts, from a_w = 0.06 m/s^2 r.m.s to a_w = 0.22 m/s^2 r.m.s. The noise level was divided into nine parts, ranging from L_{Aeq} = 45 dB(A) to L_{Aeq} = 65 dB(A), according to the maximum acceptance range [5,33]. Combined with the revised annoyance model, each annoyance rate according to noise and vibration levels is obtained in Figures 4 and 5. Each shaped dot corresponds to a specific noise level or vibration acceleration.

From Figure 4, the growth of calculated annoyance rates was relatively slow at first, and then gradually became fast as the vibration level increased. Each curve showed a similar trend when noise levels varied in the range of 45–55 dB(A), and this characteristic feature indicates that noise levels have little impact on the combined annoyance rate when the noise level was low. Maigrot P et al. [38] revealed that vibration annoyance was weakly influenced by noise level, except when the vibration level was high. The growth of each annoyance curve gradually slowed with increasing noise levels, and this variation can also be seen in Figure 5, as the vibration level increased. By comparing the variation trend of calculated annoyance rates in the two graphs, the slightly increased parts of annoyance in Figure 4 are larger than those in Figure 5, when the horizontal coordinates vary from the initial value to middle values; this difference means that the vibration level has a great impact on calculated annoyance rates before the noise level reaches 57.5 dB(A). For the noise membership function, k = 0.085, u_0 = 55 and n = 0.821. The onboard annoyance rate considering noise is derived as Equation (7). The feeling evaluation of noise and vibration was described and quantified at the level of psychophysics and psychology after considering the ambiguity of subjective judgment criteria and the difference in perception ability under vibration and noise stimulation.

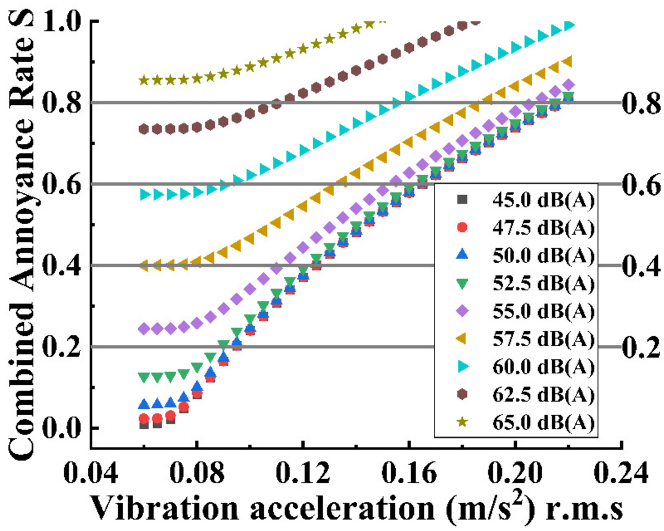

Figure 4. Influence of the vibration level on the assessment of noise.

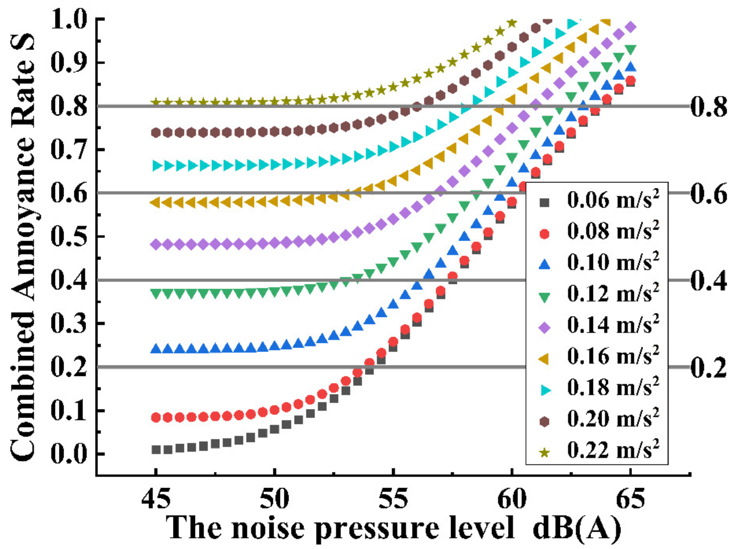

Figure 5. The influence of noise level on the assessment of vibration.

However, after reaching 57.5 dB(A), while the curves in Figure 4 maintained a constant, the calculated annoyance rate curves in Figure 5 show the close arrangement, which indicates a higher impact of noise distance. Howart HVC and Griffin MJ [39] found that noise has a greater impact on subjective coupled feelings, while annoyance is less affected by vibration. Eriksson C et al. [40] also concluded that noise annoyance is one of the most significant subjective effects in the workplace.

Based on the results of the passenger cabin, the annoyance degree E was chosen as the comfort limit with the vast majority of votes in D and E. In this degree, the vibration level should be lower than 0.095 m/s^2, and the noise level should be less than 54 dB(A), to reach slight annoyance. It is higher than the standards of crew cabin (50 dB(A)) and passenger standard cabins (45 dB(A)) from SILENV [41]. Further study is needed to reveal this difference. Based on the investigation results of the dining cabin, the annoyance degree D was chosen as the comfort limit with only 5% annoyance. The vibration level should be lower than 0.125 m/s^2 to reach moderate annoyance, as shown in Figure 4. The noise level should be less than 57.5 dB(A) to reach moderate annoyance, as shown in Figure 5.

4. Conclusions

In this paper, the combined effects of vibration and noise from ship cabins on annoyance are studied by combining on-site investigation with theoretical analysis. In theory, the revised membership function based on the equidistant perception method and exponential membership function was applied in the annoyance rate model to quantify the effects of vibration and noise on comfort. Two screening problems, the "unnoticed" choice and the transformation from an eleven-point scale to a five-point scale, were added to help subjects clarify their feelings. Continuity between annoyance theory and the investigation was achieved by designing comfort evaluation criteria (grade E- Not at all- [0, 0.2]; grade D- Slightly annoyance- [0.2, 0.4]; grade C- Moderately annoyance- [0.4, 0.6], grade B- Highly annoyance- [0.6, 0.8]; grade A-Extremely annoyance- [0.8, 1.0]).

In summary, the annoyance rate model is applicable in evaluating the comfort of vibration and noise and can basically reflect the crew's comfort feelings. When the noise level varies from 45 dB(A) to 57.5 dB(A), the vibration level has a greater impact on subjects' feelings of annoyance than the noise level. When the noise value exceeded 57.5 dB(A), the noise level had a significant influence on subjects' levels of satisfaction. In a comfortable onboard environment, the vibration level should be lower than 0.095 $m/s^{2,}$ and the noise level should be less than 54 dB(A). If the environment is not too restrictive, the recommended value of vibration should be lower than 0.125 $m/s^{2,}$ and the noise level should be less than 57.5 dB(A).

Author Contributions: Conceptualization, H.L.; methodology, Z.G; software, J.S.; validation, X.L., Z.G. and J.S; formal analysis, Z.G.; investigation, J.S.; data curation, X.L and J.S.; writing—original draft preparation, Z.G. and X.L.; writing—review and editing, H.L. and X.L.; supervision, H.L.; project administration, H.L.; funding acquisition, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Natural Science Foundation of China (No. 51406112); Natural Science Foundation of Shanghai (No. 20ZR1423300).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the ship staff and all participants in the surveys for their cooperation.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Onboard comfort questionnaire for the annoyance rate was introduced in Section 2.2.2. The detailed questionnaire is listed here.

Onboard comfort questionnaire

Date： / / （**8:30 - 12:30□ 13:00 - 18:00□** ）

Participant's basic information：

Age(years old)**：** <=19□ 20~30□ 31~40□ 41~50□ >=51□

Gender： Male□ Female□

Background： Passenger□ Crew member□ Service worker□

For the sake of developing the subject's comfort on the boat, we are now inviting you to participate in our satisfaction survey. The questionnaire is **anonymous** and **no personal characteristics will be recorded**. The questionnaire is divided into two parts, the first part is your current status and the second part is the comfort votes for thermal, vibration, noise, illumination, and the overall environment. Your votes will provide some valuable advice for our future research. Thank you for your cooperation!

Part I

Do you feel uncomfortable caused by vibration or shake? Do you think the vibration source was among hull shaking, machine vibrating, and people walking?

Yes□ No□

Do you feel uncomfortable caused by acoustics? Do you think the noise source was among waves slamming, machine noise, people walking, chatting, and so on?

Yes□ No□

If your answers to two questions are **both 'yes'**, please feel the ambient environment for **several minutes** and turn this questionnaire back to fill the questionnaire; if **at least one of your answer is 'no'**, please **give this questionnaire back** to our researchers:

Part II

How much were you annoyed for this reason? If you feel any annoyance or discomfort, please use the following scale to rate.

Source	Unnoticed	Not at all										Extremely annoying
Hull shaking		0	1	2	3	4	5	6	7	8	9	10
Machine vibration and noise		0	1	2	3	4	5	6	7	8	9	10
Wave slamming		0	1	2	3	4	5	6	7	8	9	10
Chatting		0	1	2	3	4	5	6	7	8	9	10
People walking		0	1	2	3	4	5	6	7	8	9	10
Others (please fill in below)												

Let me thank you once more and have a great trip!

References

1. Alnuman, N.; Altaweel, M.Z. Investigation of the Acoustical Environment in A Shopping Mall and Its Correlation to the Acoustic Comfort of the Workers. *Appl. Sci.* **2020**, *10*, 1170. [CrossRef]
2. Zhu, Y.; Chen, G.Q.; Li, X.L.; Lu, Y.; Liu, J.J.; Xu, T.F. Comfort assessment for rehabilitation scaffold in road-railway bridge subjected to train-bridge-scaffold coupling vibration. *Eng. Struct.* **2020**, *211*, 1–12. [CrossRef]
3. Borelli, D.; Gaggero, T.; Rizzuto, E.; Schenone, C. Analysis of noise on board a ship during navigation and manoeuvres. *Ocean Eng.* **2015**, *105*, 256–269. [CrossRef]
4. Kurt, R.E.; Khalid, H.; Turan, O.; Houben, M.; Bos, J.; Helvacioglu, I.H. Towards human-oriented norms: Considering the effects of noise exposure on board ships. *Ocean. Eng.* **2016**, *120*, 101–107. [CrossRef]
5. *IMO Resolution MSC.337(91)*; Adoption of the Code on Noise Levels on Board Ships. International Maritime Organization: London, UK, 2012.
6. Borelli, D.; Gaggero, T.; Rizzuto, E.; Schenone, C. Onboard ship noise: Acoustic comfort in cabins. *Appl. Acoust.* **2021**, *177*, 107912. [CrossRef]
7. Badino, A.; Borelli, D.; Gaggero, T.; Rizzuto, E.; Schenone, C. Criteria for noise annoyance evaluation on board ships. In Proceedings of the 14th International Congress of the International Maritime Association of the Mediterranean, Genova, Italy, 13–16 September 2012; Volume 2, pp. 971–980. [CrossRef]
8. Rocca, M.; Di Puccio, F.; Forte, P.; Leccese, F. Acoustic comfort requirements and classifications: Buildings vs. yachts. *Ocean Eng.* **2022**, *255*, 111374. [CrossRef]
9. *ISO 2631-2:2003*; Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration-Part 2: Vibration in Buildings (1 hz to 80 hz). International Organization for Standardization: Geneva, Switzerland, 2003.
10. *BS 6871:1987*; Guide to Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock. British Standards Institution: London, UK, 1987.
11. Omer, H.; Bekker, A. Human responses to wave slamming vibration on a polar supply and research vessel. *Appl. Ergon.* **2018**, *67*, 71–82. [CrossRef]
12. Liu, H.M.; Lian, Z.Z.; Gong, Z.H.; Wang, Y.C.; Yu, G.J. Thermal comfort, vibration, and noise in Chinese ship cabin environment in winter time. *Build. Environ.* **2018**, *135*, 104–111. [CrossRef]
13. Paulsen, R.; Kastka, J. Effects of combined noise and vibration on annoyance. *J. Sound Vib.* **1995**, *181*, 295–314. [CrossRef]
14. Lee, P.J.; Griffin, M.J. Combined effect of noise and vibration produced by high-speed trains on annoyance in buildings. *J. Acoust. Soc. Am.* **2013**, *133*, 2126–2135. [CrossRef] [PubMed]
15. Huang, Y.; Griffin, M.J. The relative discomfort of noise and vibration: Effects of stimulus duration. *Ergonomics* **2014**, *57*, 1244–1255. [CrossRef]
16. Huang, Y.; Li, D. Subjective discomfort model of the micro commercial vehicle vibration over different road conditions. *Appl. Acoust.* **2018**, *145*, 385–392. [CrossRef]
17. Mellert, V.; Baumann, I.; Freese, N.; Weber, R. Impact of sound and vibration on health, travel comfort and performance of flight attendants and pilots. *Aerosp. Sci. Technol.* **2008**, *12*, 18–25. [CrossRef]
18. Aladdin, M.F.; Jalil, N.A.A.; Guan, N.Y.; Rezali, K.A.M. Perturbation effect of noise on overall feeling of discomfort from vertical whole-body vibration in vibro-acoustic environment. *Int. J. Ind. Ergon.* **2021**, *83*, 103136. [CrossRef]
19. Ögren, M.; Gidlöf-Gunnarsson, A.; Smith, M.; Gustavsson, S.; Waye, K.P. Comparison of annoyance from railway noise and railway vibration. *Int. J. Environ. Res. Public Health* **2021**, *14*, 805. [CrossRef] [PubMed]
20. Belsky, J.; Pluess, M. Beyond Diathesis Stress: Differential susceptibility to environmental influences. *Psychol. Bull.* **2009**, *135*, 885–908. [CrossRef] [PubMed]
21. Ellis, B.J.; Boyce, W.T.; Belsky, J.; Bakermans-Kranenburg, M.J.; Ijzendoorn, M.H.V. Differential susceptibility to the Environment: An evolutionary- neurodevelopmental theory. *Dev. Psychopathol.* **2011**, *23*, 7–28. [CrossRef]
22. Griffin, M.J.; Whitham, E.M. Individual variability and its effect on subjective and biodynamic response to whole-body vibration. *J. Sound Vib.* **1978**, *58*, 239–250. [CrossRef]
23. Tao, Z.; Wang, Y.; Zou, C.; Li, Q.; Luo, Y. Assessment of ventilation noise impact from metro depot with overtrack platform structure on workers and nearby inhabitants. *Environ. Sci. Pollut. Res.* **2019**, *26*, 9203–9218. [CrossRef]
24. Wang, G.; Zhang, J.; Kong, X. Study on passenger comfort based on human–bus–road coupled vibration. *Appl. Sci.* **2020**, *10*, 3254. [CrossRef]
25. Pierrette, M.; Marquis-Favre, C.; Morel, J.; Rioux, L.; Vallet, M.; Viollon, S.; Moch, A. Noise annoyance from industrial and road traffic combined noises: A survey and a total annoyance model comparison. *J. Environ. Psychol.* **2012**, *32*, 178–186. [CrossRef]
26. Li, X.; Hu, Z.; Zou, C. Noise annoyance and vibration perception assessment on passengers during train operation in Guangzhou Metro. *Environ. Sci. Pollut. Res.* **2021**, *29*, 4246–4259. [CrossRef] [PubMed]
27. Ke, S.; Wei, Z. Combined annoyance assessment of subway train-induced structural vibration and ambient noise. *Shock. Vib.* **2016**, *2016*, 3028037. [CrossRef]
28. *ISO 8041-1:2017*; Human Response to Vibration—Measuring Instrumentation—Part 1: General Purpose Vibration Meters. International Organization for Standardization: Geneva, Switzerland, 2017.
29. Tu, R.H.; Zhan, J.K.; Sun, J.Q.; Fang, D.Q. An Investigation on community response to environmental vibration. *Environ. Sci.* **1990**, *11*, 70–73. (In Chinese) [CrossRef]

30. Tu, R.H. Some concepts that need urgent clarification in the current environmental vibration research work in China. *Environ. Eng.* **1993**, *11*, 50–52. (In Chinese) [CrossRef]
31. Wang, X.M.; Tang, L.G.; Liu, X.S.; Fang, F.M.; Zhao, W. Investigation of environmental noise perception of residents in Lu' an City. *J. Environ. Health* **2007**, *24*, 893–896. (In Chinese) [CrossRef]
32. *ISO 6954:2000*; Mechanical Vibration—Guidelines for the Measurement, Reporting and Evaluation of Vibration with Regard to Habitability on Passenger and Merchant Ships. International Organization for Standardization: Geneva, Switzerland, 2000.
33. *GB 5980:2009*; Regulation on Noise Levels on Board Inland Ships. CHINESE GB Standards: Beijing, China, 2009.
34. *ABS 103:2014*; Guide for Passenger Comfort on Ship. American Bureau of Shipping: Houston, TX, USA, 2014.
35. *BS EN ISO 11904-2: 2004*; Acoustics Determination of Sound Emission from Sound Sources Placed Close to the Ear–Part 2: Technique Using a Manikin. The London Declaration: London, UK, 2004.
36. *ISO/TS 15666:2021*; Acoustics-Assessment of Noise Annoyance by Means of Social and Socioacoustic Surveys. International Organization for Standardization: Geneva, Switzerland, 2021.
37. Fleming, D.B.; Griffin, M.J. A study of the subjective equivalence of noise and whole-body vibration. *J. Sound Vib.* **1975**, *42*, 453–461. [CrossRef]
38. Maigrot, P.; Parizet, É.; Marquis-Favre, C. Annoyance due to combined railway noise and vibration: Comparison and testing of results from the literature. *Appl. Acoust.* **2020**, *165*, 1–8. [CrossRef]
39. Howart, H.V.C.; Griffin, M.J. Subjective response to combined noise and vibration: Summation and interaction effects. *J. Sound Vib.* **1990**, *143*, 443–454. [CrossRef]
40. Eriksson, C.; Pershagen, G.; Nilsson, M. Biological Mechanisms Related to Cardiovascular and Metabolic Effects by Environmental Noise. WHO Environmental Noise Guidelines for the European Region 2018 1–9. Available online: https://www.euro.who.int/__data/assets/pdf_file/0004/378076/review-noise-bio-effects-eng.pdf (accessed on 1 January 2022).
41. *SILENV 2012*; WP 5: Green Label Proposal—Subtask 5.2: Noise and Vibration Label Proposal. SILENV: Paris, France, 2012.