International Journal of Ocean Engineering and Technology, Vol. 3, No.1, pp 56~62, April 2000 (ISSN 1229-1668)

An Improvement Method of Sound Quality of the High-speed Coastal Passenger Ship

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(Received 18 February 2000, accepted 17 April 2000)

KEY WORDS: Sound quality, Passenger ship, Noise reduction, Loudness, Roughness, Fluctuation strength, Sharpness, Critical frequency band

ABSTRACT: *The trends of recent passenger ships are becoming speedy and luxury style to enhance comfortableness in cabin. In order to meet these trend, ship designer has to improve the sound quality as well as to reduce the sound pressure level in cabins. In this paper, the trend of noise and sound quality of real high-speed coastal passenger ships are measured and analyzed, while running on their regular courses. The sound quality parameters such as loudness, roughness, fluctuation strength, and sharpness are evaluated by Zwicker loudness calculation. In addition, we try to find sensitive critical frequency band for the improving sound quality by using signal editing. Finally, the expected effective design methods are proposed to designer for the improving sound quality of passenger ships.*

1. Introduction

One way to recognize the acoustic signals is to divide it into noise and sound. Noise is measured for avoiding hearing damages and fulfilling regulations, legislation. On the other hand, sound relates much more to the human perception and content of information received by the listener.

Sound power and sound pressure measurements are the traditional, simple and fast way for characterizing the acoustical behavior of products. But these are not enough for evaluation of sound. Sound quality is a newer discipline. It is not so well described in standards yet. But this can give much better results to be correlated with the human perception. Sound quality parameters are based on the principles developed within the interdisciplinary science of Psycho-acoustics. This allows quantitative evaluation of subjective sound sensations. It permits engineers and technicians to analyze and manipulate product noise in order to achieve desired or optimum sound. The first priority of sound quality is to stand target sound before the rework or new products developments. It gives them predictive results without restructuring. In recent years, the focus on sound quality has spread to most of industries producing products that generate noise (Bruel & Kjaer Technical Note, 1997; Ryu, *et al.*, 1997).

In the field of shipbuilding, many research activities for noise reduction are doing well and continuing. But these researches are mainly concerned with sound pressure level for fulfilling the noise recommendation. And these results couldn't be heard before the new construction or reconstruction of ships. But the sound quality evaluation system makes it possible to do so. From the sound quality tested on the existing ships, we can get target sound for the effective noise reduction.

The passenger ships have difficult problems of noise reduction, because the noise source is very closely installed to receiver compared with large merchant ships and its main components of noise are generated at the low frequency bands. But, the trends of recent passenger ships are becoming speedy and luxury style in cabin. In order to meet these trends in the passenger ship, the reduction of sound pressure level must be the first design target, but it is usually not enough for passengers requirements. Because most passengers desire not only transportability but also more comfortable environments in cabin, sound quality should be considered.

In this paper, as the first step to control the sound quality, the trend of noise and sound quality of real passenger ships are measured and analyzed, while running on their regular courses. And we calculated the sound quality parameters such as loudness, roughness, fluctuation strength, and sharpness by Zwicher loudness calculation. We try to find sensitive critical frequency band for the improving sound quality by using signal editing. Finally, the expected effective design methods are proposed to designer for the improving sound quality of passenger ships.

2. Psycho-acoustics

The sensitivity of our hearing system is not linear to the amplitude and frequency of sound. To reveal the amplitude dependency to hearing frequency response, Eberhart Zwicker[1] had sound perception tests for wider amplitude and frequency ranges

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[1] Psycho-acoustician, Professor Univ. Munchen

of sound pressure levels. Fig. 1 shows several equal loudness curves for sinusoidal signals normalized around 1 kHz. At low amplitudes the A-weighting curve is a reasonable approximation of the ears frequency response. At higher amplitudes, however, A-weighting over-attenuates So, loudness level is dependent on the amplitude as well as frequency(Hassall, J. R., *et al.*,1988).

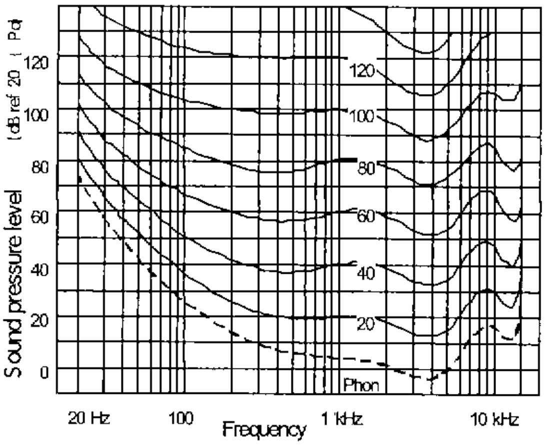

Fig. 1 Equa loudness curve

Frequency masking occurs due to the human hearing mechanism. In human inner ear, the cochlea acts as a bank of 24 band-pass filters with different sections of its length responding to different frequency ranges. These frequency ranges are referred to as critical bands. The band is named as 'Bark'. A critical band can be defined anywhere along the audible frequency range and its bandwidth is defined by where *ft* is the band center frequency in Hertz.

$$\Delta f = 25.0 + 75.0 \times \left[1.0 + 1.4 \times \left(\frac{ft(Hz)}{1000}\right)^2\right]^{0.69} Hz \qquad (1)$$

At frequencies close to the frequencies of the narrow-band noise, additional even tonal sound having equal or greater amplitude may be inaudible. However, tonal sounds of much lower amplitude having quite different frequency compared with the frequencies of the narrow-band noise are detectable. The limit of detection ability is known as the masked threshold.

The Fig. 2 shows the thresholds of pure tones masked by critical-band wide noise at center frequencies of 250Hz, 1kHz and 4kHz. The level of each masking noise is 60 dB and the corresponding bandwidths of the noise are 100,160 and 700Hz, respectively. The shape of the masking threshold shows the frequency dependency definitely. And maximum of the masked threshold shows the tendency to be lower for high center frequencies of the masker, although the level of the narrow-band masker is 60dB at all center frequencies. Masking effects are also dependent on amplitude. In addition, sounds are masked not only in the frequency domain but also in the time domain. Temporal masking is produced, as the basilar membrane requires time interval to perceive the successive sound. We are hearing the sound through the combination of these phenomena(Zwicker and Fastl, 1999).

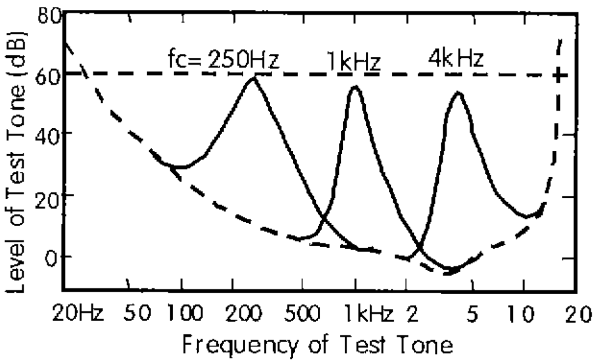

Fig. 2 The shape of the masking threshold

3. Sound Quality Parameters

In this paper, Zwicker loudness calculation method is adopted for the evaluation of ship sound quality. In the method, loudness, fluctuation strength, roughness and sharpness are used as sound quality parameters. They are reflecting most of the psycho-acoustic properties of the human perception of sound. These parameters are defined as follows.

Loudness; Loudness is a measure for how loud or how soft a sound is heard relative to a standard sound. Loudness quantifies the perceived intensity of a sound. It is a linear measure of the magnitude of auditory sensation. The unit of loudness level is Sone or Phon. One Sone means the loudness due to a 1000 Hz pure tone with a sound pressure level of 40 dB. The relation between Sone and sound pressure level is

$$N = 2^{(P-40)/10} \qquad SONE \qquad (2)$$

where P is the sound pressure level(dB). Phon represents the loudness level calculated using Sone value as

$$P = 40 + 10\log_2 N \qquad Phon \qquad (3)$$

Loudness calculator of Method B developed by Zwicker is designed to be used with third octave band measurements. This method can be applied for free field or diffuse field masurements.

Roughness; Roughness measures the amount of modulation of a particular signal having its modulation frequencies between 15 Hz and 300 Hz. Roughness is measured in *aspers*. The roughness of 1 asper is defined as a 60 dB, 1000 Hz pure tone that is 100% modulated in amplitude at a modulation frequency of 70 Hz. The roughness R of any sound is calculated as

$$R=0.3f_{\mathrm{mod}}\int_{0}^{24Bark}\frac{\Delta L_E(z)dz}{dB/Bark} \qquad asper \tag{4}$$

where f_{mod} is modulation frequency in kHz and $\Delta L_E(z)$ is temporary masking effect depth at each Bark band.

Fluctuation Strength; Fluctuation strength measures the modulation amount of a signal. This is calculated for modulation frequencies below 15 Hz and measured in *vacils*. Fluctuation strength can be measured directly from the specific loudness amplitude envelopes using the equation

$$F\approx\frac{\Delta L}{(f_{\mathrm{mod}}/4Hz)+(4Hz/f_{\mathrm{mod}})} \tag{5}$$

where ΔL is the masking depth of the temporal masking pattern, not the sound pressure envelope, which varies as a function of modulation frequency due to the temporal aspect of loudness. The basic terms and formulas are involved in a calculation of fluctuation strength. Using the boundary condition that a 60 dB, 1kHz tone which is 100% amplitude-modulated at 4 Hz produces a fluctuation strength of 1 vacil. The fluctuation strength is a sum of all specific fluctuation strengths as

$$F=\sum^{24}F(z) \qquad vacil \tag{6}$$

Sharpness; Sharpness is a linear measure of the high-frequency content of an acoustic signal. Sharpness is measured in acums. A sharpness of 1 acum is defined as a narrow-band noise around 1000 Hz with a bandwidth lower than 150 Hz at 60 dB SPL. The sharpness was defined as

$$S=0.11\frac{\int_{1}^{24}N(z)\cdot g(z)\cdot z\cdot dz}{\int_{1}^{24}N(z)\cdot dz} \qquad acum$$

$$g(z)=\begin{pmatrix} 1 & \text{for } z\leq 16 \\ 0.066\cdot e^{0.171\ z} & \text{for } z\geq 16 \end{pmatrix} \tag{7}$$

In this equation, S is the sharpness to be calculated and the denominator gives the total loudness N. The upper integral *represents the first moment of the specific loudness over* critical-band rate. Only for critical-band rates larger than 16 Bark, the factor increase from unity to a value of four at end of the critical-band rate near. The value *g(z)* is a weighting function that emphasizes levels in the higher frequency critical bands.

The human perception of sound is a very complex process and highly non-linear. That calls for other acoustical descriptors than those used in normal linear sound work(Bruel & Kjaer Technical Note, 1997; Zwicker and Fastel, 1999).

Table 1 Data of test ships and measurement conditions

Ship	A	B	C	D	E
Date of Launch	Mar,'90	Jul,'92	Apr,'95	Mar,'94	Dec,'95
Gross tonnage (ton)	279	290	228	273	131
Standard class	346	294	306	280	145
Speed (Knot)	40	40	40	40	32
Power (KW)	3,200	3,360	4,000	4,000	2,941
Length (m)	32.55	31.50	37.03	37.74	26.43
Breadth (m)	11.50	11.30	10.10	9.30	7.20
Depth (m)	3.50	3.53	3.97	3.47	2.53
Propulsion type	Water jet				Propeller
Service Line (mile)	Coastal line(24)				(32)
Weather conditions	Clear	Clear	Clear After Cloudy	Cloudy	Clear
Wind direction	NE- SE	NE- SE	NE-SE	NE-SE	NE- SE
Wind Speed (m/s)	7 ~ 11	6~10	7 ~ 11	7 ~ 11	6~10
Wave (m)	1.5 ~ 2	1.5~2	1.5 ~ 2	1.5 ~ 2	1.5~2

4. Sound Quality Test Setups

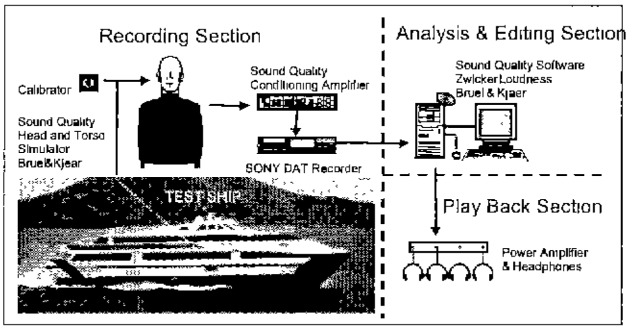

Fig. 3 The sound quality testing and evaluation system

The sound quality testing and evaluation systems are shown in Fig. 3. The system can be split up into three parts as recording, analysis and editing, and playback sections.

In the recording section, we recorded the sound binaurally using a Bruel & Kjaer head and torso simulator at the middle of cabin to consider the human hearing system. And we also used the diffuse field correction filter in conditioning amplifier. All the time signals were recorded up to 25.6 kHz in digital data recorder. The measurements were carried out in five high-speed passenger ships, so called coastal liners. Main particulars of the ships and measurement conditions are represented in Table 1. All the measurements were carried out while the ship was running on normal cruising speed and the measurement system was calibrated and adjusted before and after measurement. Each test was performed under the almost same weather condition. During the whole measurement, all speakers were turned off and passengers were kept quiet.

5. Sound Quality Evaluation

In the analysis and editing section, we used the Bruel & Kjaer sound quality software based on Zwicker loudness calculations. The time signal was inputted to PC hard disk via high performance sound card from the digital recorder.

In the play back section, by using the 1kHz reference signal recorded on digital recorder, we carried out system calibration and play back calibration before analysis.

Sound pressure of each test ship has been analyzed by traditional way in advance. Overall sound pressure levels and A-weighted 1/3 octave analysis results are shown in Fig. 4, 5. And the objective results of sound quality evaluation are shown in Fig. 6~9. The loudness spectrum and the correlation between sound pressure level (SPL) are shown in Fig. 10 and Fig. 11, respectively. From these resluts we can find that the loudness levels are almost proportional to A-weighted SPL in all test ships. This is because that A-weighting curve is derived from an equal loudness curve. But the others sound quality parameters are difficulty to define the relation with SPL.

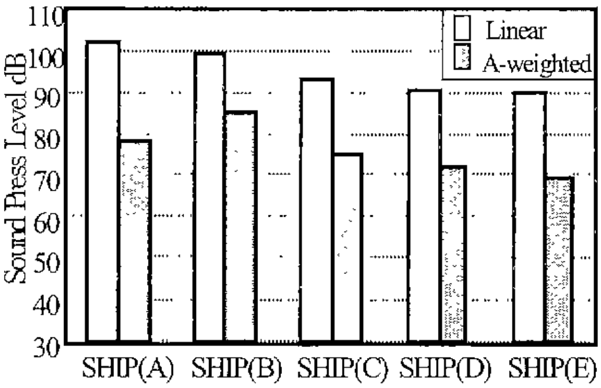

Fig. 4 A-weighted and linear overall sound pressure level

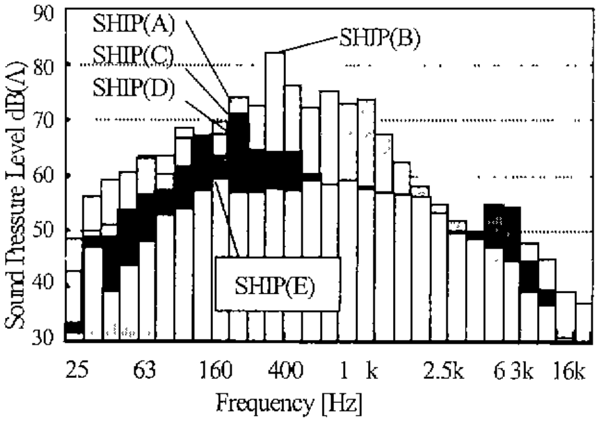

Fig. 5 A-weighted sound pressure spectrum in 1/3 octave

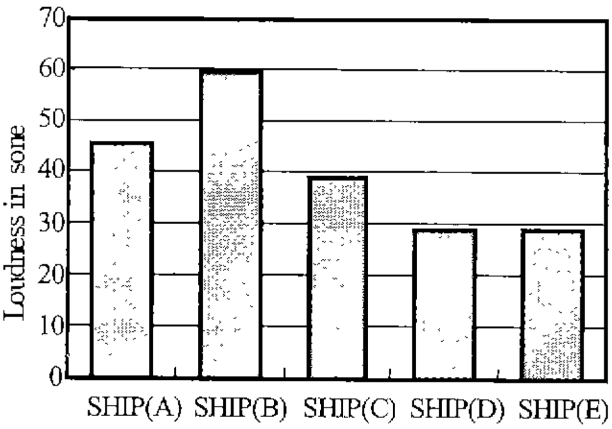

Fig. 6 Mean total loudness

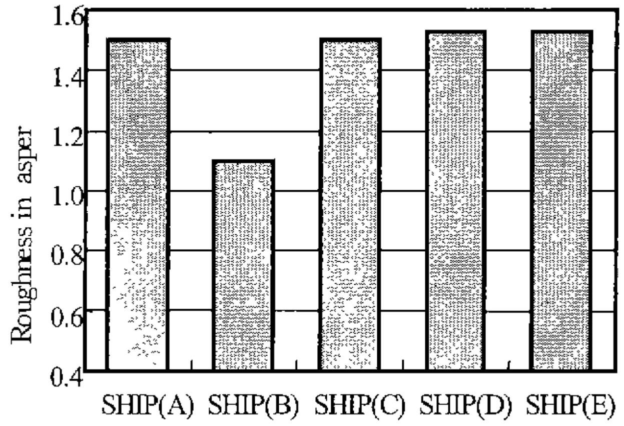

Fig. 7 Roughness

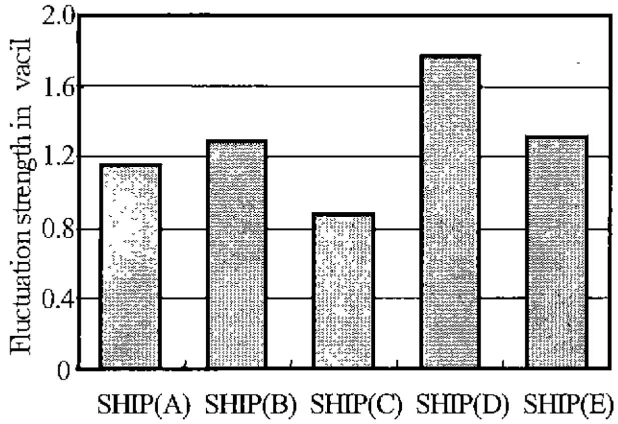

Fig. 8 Fluctuation strength

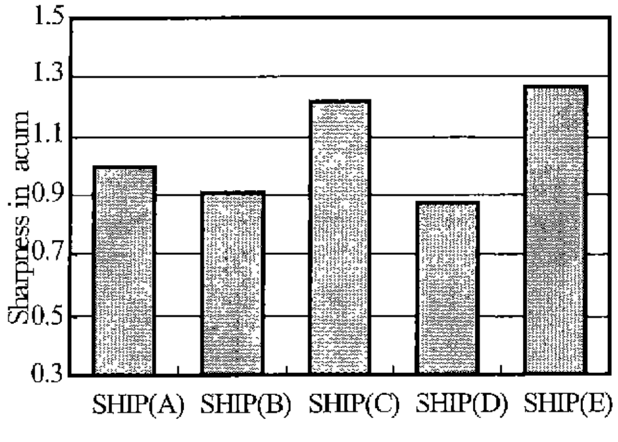

Fig. 9 Mean sharpness

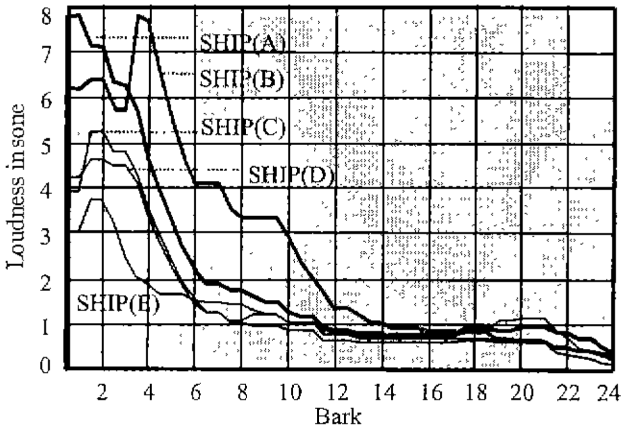

Fig. 10 Loudness spectrum

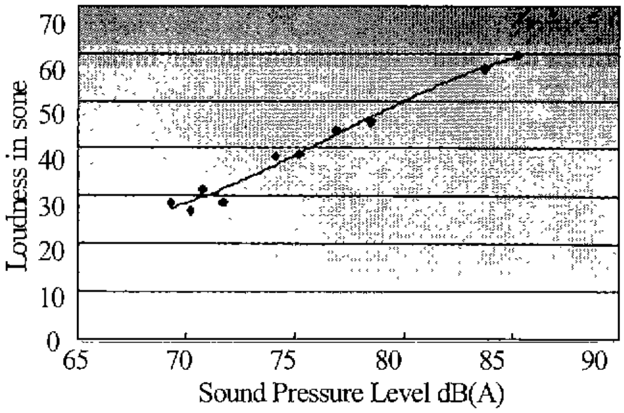

Fig. 11 Trend of loudness compare to sound pressure level

The ship B shows the highest A-weighted overall SPL and the lowest roughness level in all test ships. This is because the temporary masking effect depth to be small at a modulation frequency of 70Hz around. In the ship C, its fluctuation strength is the lowest due to the small amplitude of the modulation frequencies below 15Hz. The SPL of ship D and E are relatively low but their roughness and fluctuation strength are high. These mean that roughness, fluctuation strength and sharpness level are high in the ships experiencing low sound pressure levels.

Generally, 1/3 octave analysis of SPL is simple and fast way for finding the major frequency components of SPL. But these dont give the information required for sound quality improvement. Maximum peak frequency, its 1/3 octave band center frequency and critical frequency band in bark are represented in Table 2. From the results, we can know that maximum SPL in the test ships are occurred at the relatively low frequency ranges, which is due to ship propulsion system. Usually, reducing the noise at low frequency is difficult problem or couldnt handle it due to the possibilities of ship operating factors in act. And also the reduction of fluctuation noise component is very difficult because the cabin is closely located to the propulsion system that is a dominant noise source in these kinds of small passenger ship.

Table 2 Maximum peak frequency from frequency analysis and 1/3 octave analysis

Test Ship	Peak Freq	1/3 Octave Center Freq.	Critical Band In Bark
SHIP(A)	176 Hz	160 Hz	2 Bark
SHIP(B)	340 Hz	315 Hz	4 Bark
SHIP(C)	190 Hz	200 Hz	2 Bark
SHIP(D)	188 Hz	200 Hz	2 Bark
SHIP(E)	161 Hz	160 Hz	2 Bark

6. A Method to Improve Sound Quality in Ship Cabins

In contrast to low frequency component, noise control of high frequency component in cabin is relatively easy. For an example, it can be achieved if high absorbent materials are used. We reduced the signal at each bark band for finding an effective solution to improve sound quality. Then, we tried to find the most sensitive critical frequency bands of the sound quality parameters by using the Zwichker loudness calculation of these edited signals. The variations of sound quality parameters in case of the 3 dB reduction of SPL at each bark are calculated. Using the results,

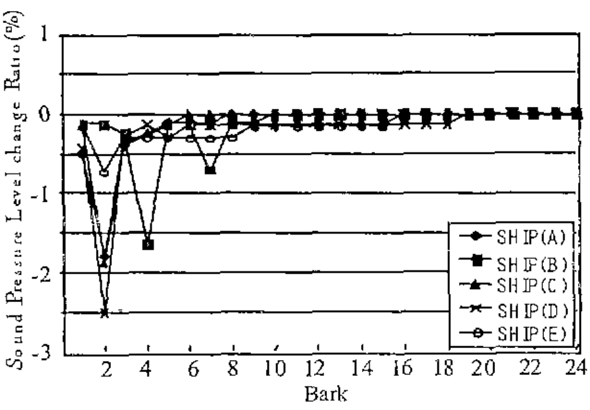

Fig. 12 Sensitivity of sound pressure level at each bark

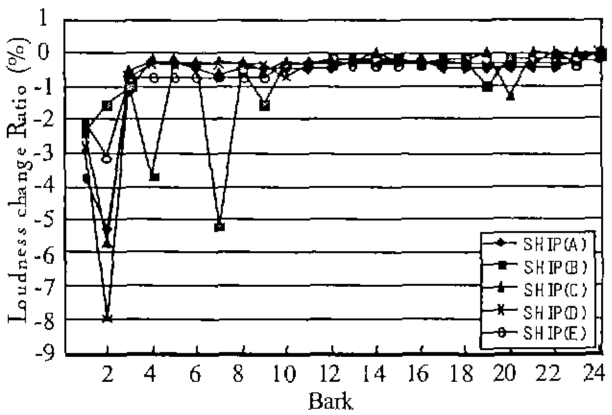

Fig. 13 Sensitivity of loudness at each bark

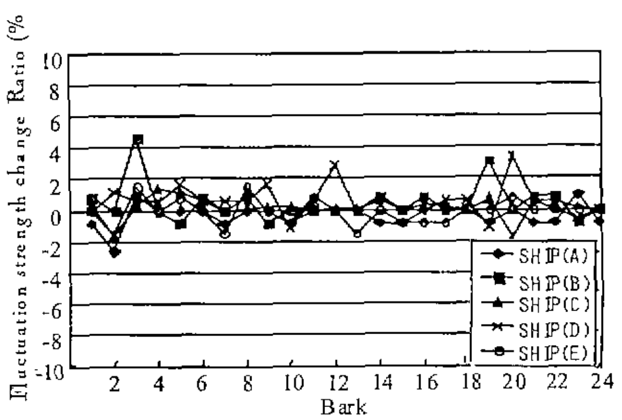

Fig. 14 Sensitivity of fluctuation strength at each bark

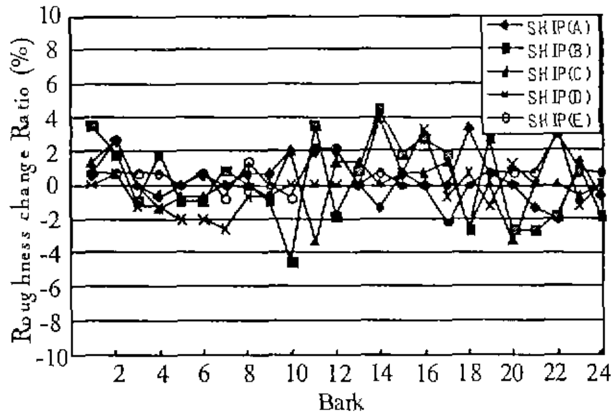

Fig. 15 Sensitivity of roughness at each bark

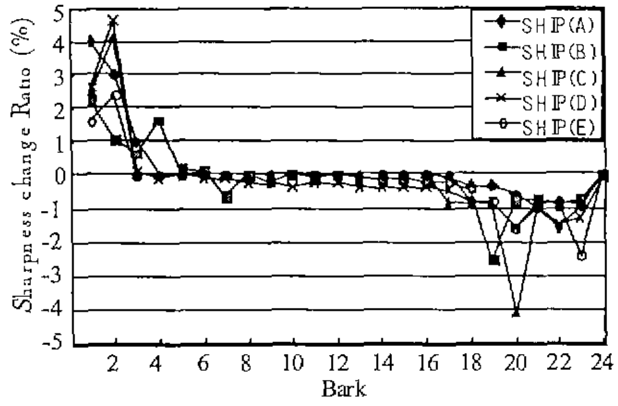

Fig. 16 Sensitivity of sharpness at each bark

we obtained sensitivity of each sound quality parameter for SPL as

$$\begin{aligned} &\textit{Change ratio } (\%) = ((OSV\text{-}ESV)/OSV)\times 100 \\ &\quad OSV : \textit{zwicker loudness calculated value from original signal} \\ &\quad ESV : \textit{zwicker loudness calculated value from - 3dB edited signal} \end{aligned} \tag{8}$$

The results are shown in Fig. 12~16 and the most sensitive critical frequency bands are represented in Table 3.

From the sound quality parameters of the edited signals, we can get the effective sensitivity frequency band at each sound quality parameters. Sound pressure level and loudness are highly sensitive between 2 bark and 7 bark.

Table 3 The most sensitive critical frequency bands of sound quality parameters (Unit: Bark)

	SHIP(A)	SHIP(B)	SHIP(C)	SHIP(D)	SHIP(E)
SPL	2	4	2	2	2
Loudness	2	4	2	2	2
Sharpness	21	19	20	20	23
Roughness	22	10	20	7	17
Fluctuation strength	2	5	20	1	7

And its trends are similar also. It means that reducing the noise at low frequency improves loudness and SPL. But it embosses the other sound quality parameters. As results, it may deteriorate sound quality in ship cabins, especially sharpness.

The sensitivities between 8 bark and 18 bark dont show some clear patterns. It means the SPL reduction in the frequency ranges has little influence to sound quality parameters. This is because the SPLs are low in these frequency ranges.

For the frequency ranges from 19 bark to 23 bark, the sharpness sensitivities to SPL reduction are high in all test ships because of the sharpness level to be mainly related to the high frequency components. The variation trend of sharpness is hardly defined due to their dispersion. But we can find it was low at ships showing higher loudness. This means that sharpness may cause the unpleasant sound at quite ships. Hence, more quite and good sound environments in cabins can be achieved if the surface material having the better absorbing property in high frequency ranges is used. But it may be difficult to improve the fluctuation strength and roughness in small ships, without the isolation of the structure-borne noise and the fluctuation of propelling power.

7. Conclusion

We can obtain the following conclusions through the sound quality test and analysis for coastal liners.

(1) Loudness levels have linear correlation with SPL and are the most sensitive from 2 bark and 4 bark.

(2) Reducing the noise at low frequency reduces loudness and SPL. But it may deteriorate the other sound quality parameters, especially sharpness.

(3) Reducing the noise at high frequency reduces sharpness, which is sensitive from 19 bark to 23 bark. As a result, sound quality of ship cabin can be improved if the surface material having the better absorbing property in high frequency ranges is used

(4) Sound quality test is expected as a useful tool for improving sound environment of ship cabins.

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