〈Original Paper〉

The Sound Quality Evaluation of High-speed Coastal Passenger Ships

고속 연안 여객선의 음질 평가

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Key Words : Sound Quality(음질), Passenger Ship(여객선), Noise Reduction(소음 저감), Noise Source(소음원) Loudness (음의 크기), Ship Motion(선체 운동), Fluctuation of Propelling Power (추력 변동)

ABSTRACT

Recently, it becomes to be very important to reduce the cabin noise of passenger ship, according to the trend of speedy and luxury ship. The noise reduction and control techniques should be considered as important factors from the viewpoint of the sound problem of cabin. Therefore, ship designer has to improve the sound quality as well as to reduce the sound pressure level in cabins. In this paper, for the new approach of these problems, we tried to find the trends of noise and sound quality of high-speed coastal passenger ships. Loudness, roughness, fluctuation strength, and sharpness are selected as the parameters for the evaluation of sound quality. The parameters are calculated by using the sound measured in cabin while the ship is running. Furthermore we tried to find the trend of each parameter in cabins and compare with that of sound pressure level. As results, we find that the loudness is linearly proportional to sound pressure level. But, the other parameters show different trends which may be caused by ship motion on the wave and fluctuation of propelling power.

요 약

최근 여객선이 고속화, 고급화되고 있는 추세에 따라 선실내 소음 저감이 중요한 설계 요소로 간주되고 있다. 일반적으로 선박 소음은 음압레벨로 평가되나 여객선의 경우 승객에게 더욱 쾌적한 환경을 제공하기 위하여 음질을 개선할 필요가 있다. 본 연구에서는 연근해를 운항 중인 기존 고속 여객선의 소음을 계측하고, 정신음향학 분야에서 제시된 Zwicker Loudness 계산식에 의거하여 음의 크기, 거칠기, 변동세기 및 날카로움으로 음질을 평가하였다. 또한, 각각의 음질 평가요소와 음압간의 상관관계를 분석하였다. 상기 결과로부터 고속여객선의 음의 크기는 음압과 비례하는 반면에 음의 거칠치(roughness), 변동세기(fluctuation strength) 및 날카로움(sharpness)은 선박의 운동과 추력변동 등으로 인하여 음압과 비선형적인 상관관계를 나타냄을 확인하였다.

1. Introduction

One way to recognize the acoustic signals is dividing it

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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 inter-disciplinary 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. Applications of sound quality are mainly progressing in the automotive industry. The first priority of sound quality is to stand target sound before the new car's developments are progressed in the mass product line. It gives them predictive results without restructuring. In recent years, the focus on sound quality has spread to most of industries producing products that make noise[1, 2].

In the 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 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 passenger's requirements. Because most passengers desire not only transportability but also more comfortable environments in cabin, sound quality should be considered to make the more comfortable environment.

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 it is not so easy to control the sound quality in cabin of passenger ship due to the possibilities of ship operating factors in act. But, it is necessary to control the sound quality in ship cabins for the more comfortable environment.

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 evaluated the sound quality parameters such as loudness, roughness, fluctuation strength, and sharpness and investigated their correlation to sound pressure level. Finally, the expected effective design methods are proposed to designer for a good 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* had sound perception tests for wider amplitude and frequency ranges of sound pressure levels. Figure 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 [3].

Frequency masking occurs due to the human hearing

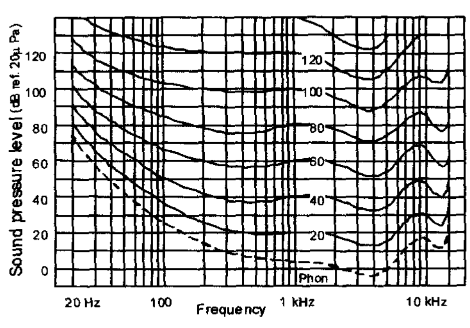

Fig. 1 Equal loudness curve

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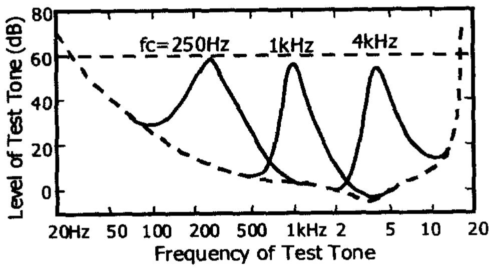

Fig. 2 The shape of the masking threshold

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

$$\Delta f = 2.50 + 75.0 \times \left[1.0 + 1.4 \times \left(\frac{ft(Hz)}{10000}\right)^2\right]^{0.69} \quad (1)$$

where ft is the band center frequency in Hertz.

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 250 Hz, 1 kHz and 4 kHz. The level of each masking noise is 60 dB and the corresponding bandwidths of the noise are 100,160 and 700 Hz, 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 60 dB 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.[4]

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

$$N = 2^{(P-40)/10} \quad Sone \quad (2)$$

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

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

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 measurements.

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

$$R = 0.3 f_{\text{mod}} \int_0^{24Bark} \frac{\Delta L_E(z)\,dz}{dB/Bark} \quad asper \quad (4)$$

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

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

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, 1 kHz 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

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

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-bond noise around 1000 Hz with a bandwidth lower than 150 Hz at 60 dB SPL. The sharpness was defined as

$$S=0.11\frac{\int_1^{24} N(z)\cdot g(z)\cdot z\cdot dz}{\int_1^{24} N(z)\cdot dz}\,acum$$

$$g(z)=\begin{cases} 1 & for\ z\le 16 \\ 0.066\cdot e^{0.171\cdot z} & for\ z>16 \end{cases} \qquad (7)$$

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[1,4].

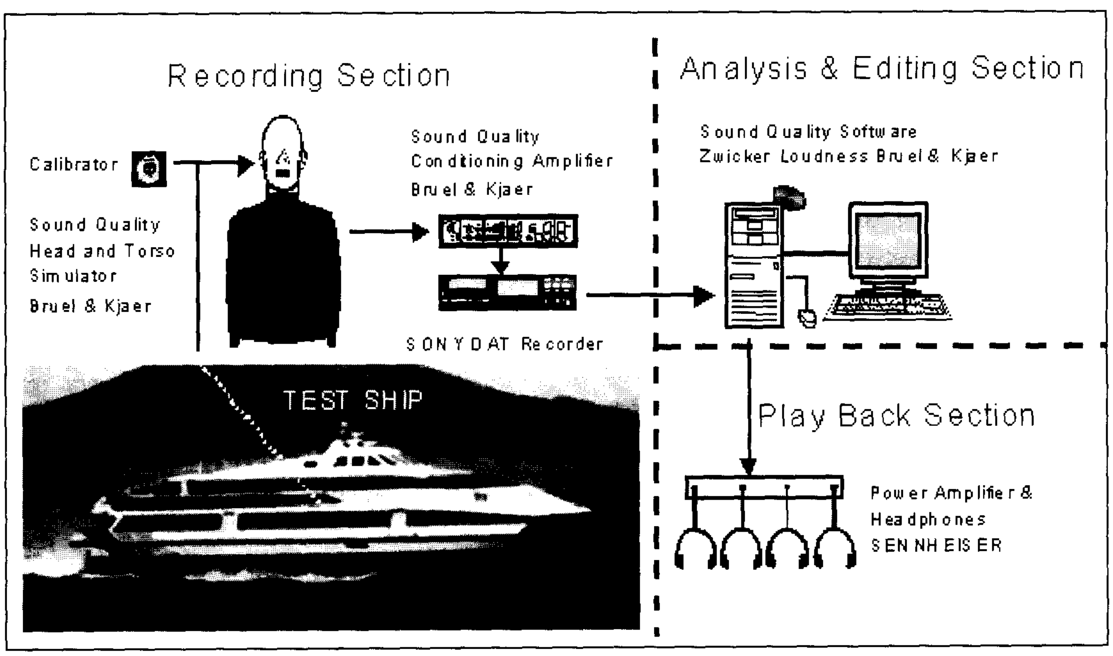

Fig. 3 The sound quality testing and evaluation system

4. Sound Quality Test Setups

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. We set up each section as follows.

In the recording section, we recorded the sound binaurally using a Brüel & Kjær head and torso simulator at the middle of cabin in due consideration of 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.

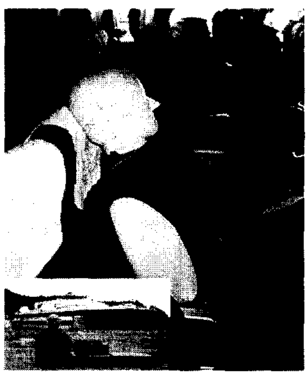

Photo 1 Photograph of the sound quality measurement

Table 1 Data of test ships and measurement conditions

Ship	A	B	C	D	E
Date of launch	Mar. '90	Jul. '92	Apr. '05	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
Proportion 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

In the analysis and editing section, we used the Brüel & Kjær sound quality software based on Zwicker loudness calculations. The time signal was inputted to PC hard disk via sound card from the digital recorder. The sampling rate of the sound card was 48,000 sampling per second.

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

All 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. We also measured the floor vibration of cabins for comparing with sound and vibration. 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. Results and Discussions of Sound Quality Analysis

Sound pressure of each test ship has been measured by traditional way in advance. Overall sound pressure levels and their frequency spectrums in 1/3 octave band are shown in Fig. 4 and Fig. 5, respectively. From the results, it is shown that noise is dominant at low frequency ranges under the 500 Hz.

The evaluation results of sound quality parameters are shown in Figs.6~9. From these results, we can find that the loudness levels are almost proportional to A-weighted SPL(sound pressure level) in all test ships. Especially, 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 70 Hz around. In the ship-C, its fluctuation strength is the lowest due to the small amplitude of the modulation frequencies below 15 Hz. The SPL of ships D and E are relatively low but their roughness and fluctuation strength are high. These mean that roughness, fluctuation strength and sharpness

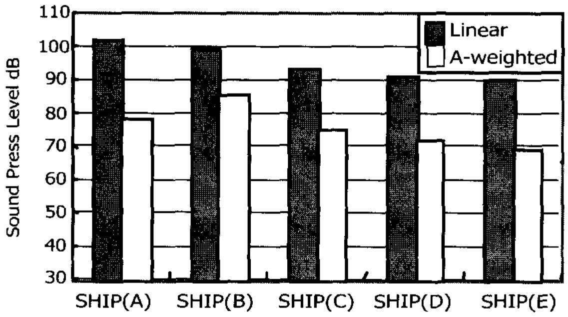

Fig. 4 A-weighted and linear overall sound pressure level

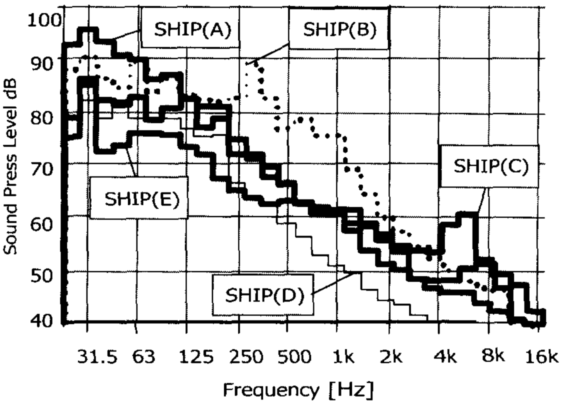

Fig.5 1/3 octave analysis data

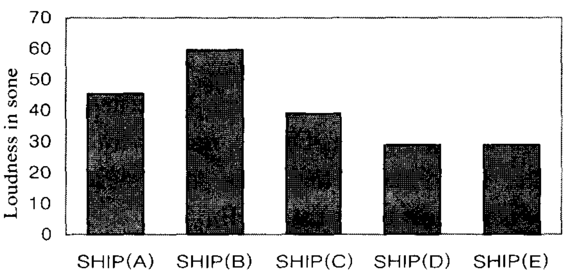

Fig. 6 Mean total loudness

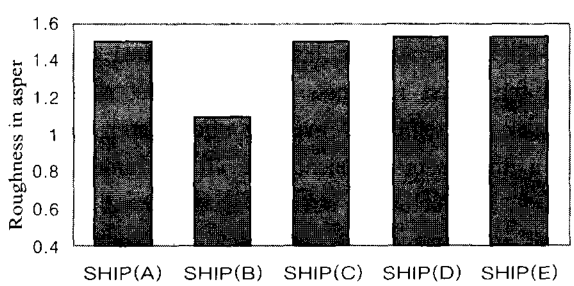

Fig. 7 Roughness

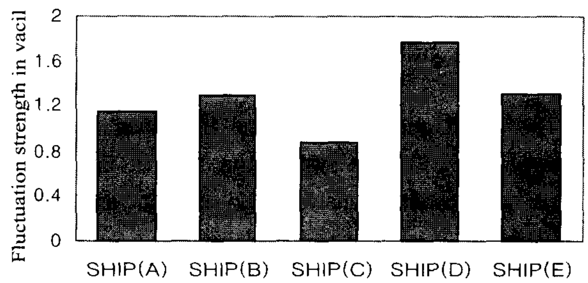

Fig. 8 Fluctuation strength

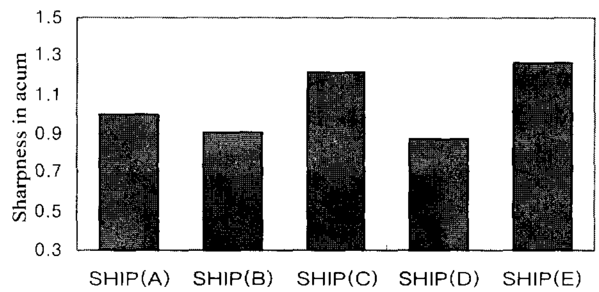

Fig. 9 Mean sharpness

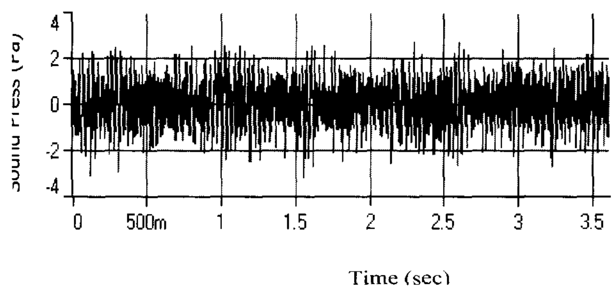

Fig. 10 Time signal of ship-board noise measured in ship C

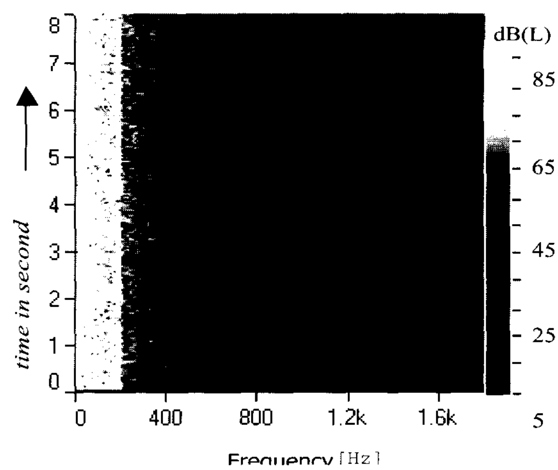

Fig.11 Contour map of the noise frequency spectrum in ship C

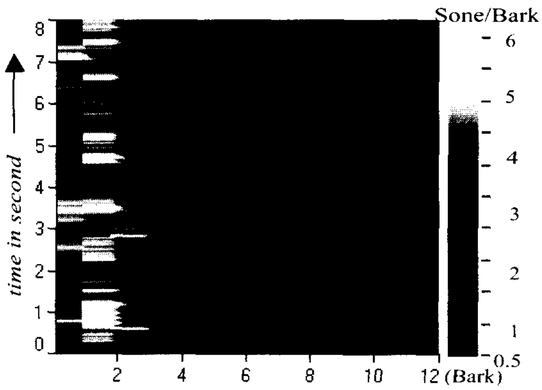

Fig. 12 Contour map of the loudness spectrum measured in ship C

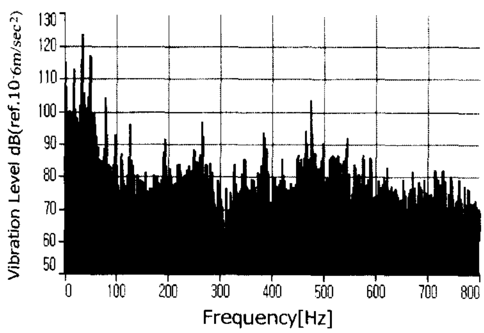

Fig. 13 Frequency spectrum of the floor vibration measured in ship C

level are high in the ships experiencing low sound pressure levels.

Time signal of ship-board noise measured in ship C is representatively shown in Fig. 10. The sound pressure signal tends to be modulated, which may be caused to ship motion occurring the fluctuation of propelling power. To evaluate the modulation effect of SPL, the frequency and loudness spectral maps on time domain are shown in Figs. 11~12. From the results, loudness levels are dominantly fluctuated between 2 Bark and 4 Bark, which is also caused to the fluctuation of propelling power. This phenomenon is also observed in the floor vibration spectrum shown in Fig. 13. This is the cause of the high roughness and fluctuation strength at low frequency ranges in the ship cabins. The reduction of fluctuation noise component may be very difficult because the cabin of small passenger ship is closely located to the propulsion system that is a dominant noise source.

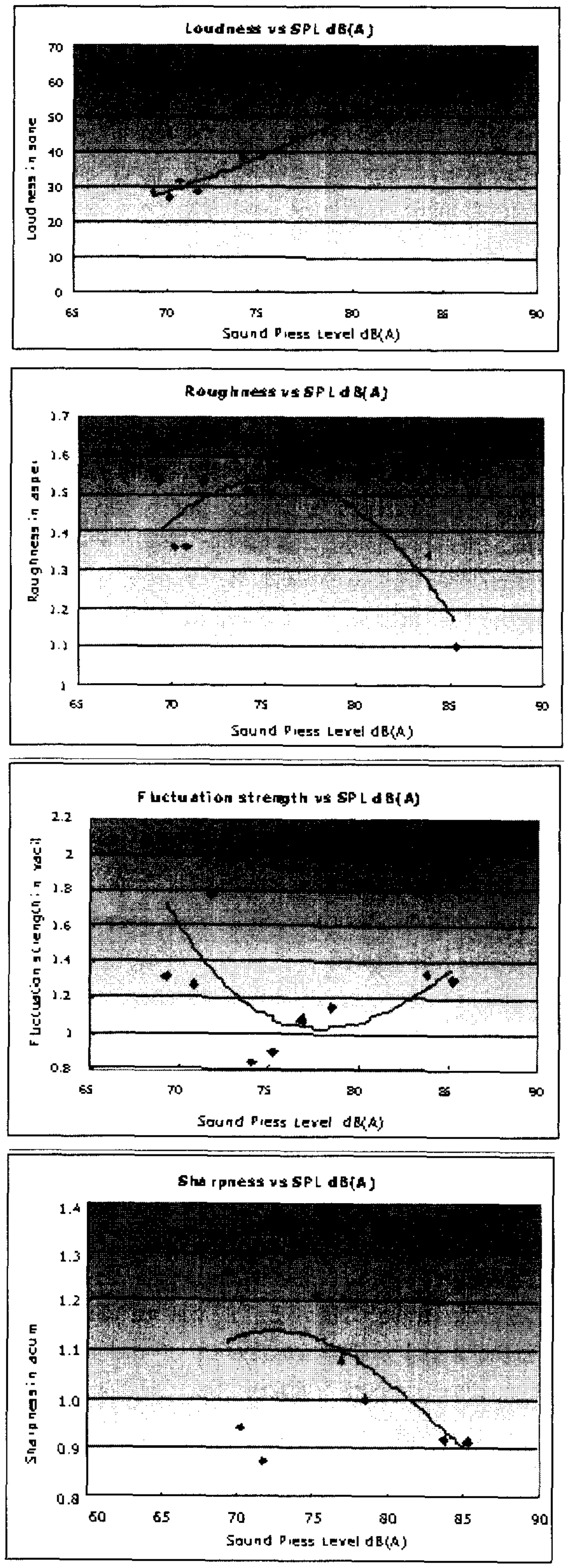

Fig. 14 Sound quality parameters compared with the sound pressure levels

In Fig. 14, sound quality parameters are compared with SPL. From the figures, it is shown that the loudness levels and the SPL have almost linearcorrelation. But the other parameters show some different trends. In the ships experiencing relatively low sound pressure, fluctuation strength, roughness and sharpness levels are relatively high. This means that the high loudness level masks the other sound quality components.

Sharpness level is mainly related to the high frequency components. The trend of sharpness is hardly defined due to their dispersion. But we can find it was low at higher loudness ships. 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.

6. Conclusion

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

(1) The relation between SPL and sound quality parameter could be cleared.

(2) Loudness levels have linear correlation with SPL. But roughness, fluctuation strength, and sharpness show some different trends.

(3) Sharpness levels should be reduced for better sound environment of ship cabin. This can be achieved if the surface material having the better absorbing property in high frequency ranges is used.

(4) Passenger ship has fluctuation sound due to ship motion on the wave. Therefore, it will be difficult to improve the sound quality parameters of the roughness and fluctuation strength without the isolation of the structure-borne noise.

(5) For the ship designers, this sound quality test may be a useful solution to meet the target sound.

Acknowledgment

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