Experimental Research on Sound Quality Characteristics of Loaders under Variable Operating Conditions

Zhanlong Li, Huangtao Bi, Wenwen Jiang, Zheng Zhang, Yong Song, and Jie Meng

Abstract—**Construction machinery plays a pivotal role in the industrial advancement of China, yet it also contributes to noise pollution that may adversely affect the auditory health of operators. Consequently, there is an increasing demand for enhancing the sound quality of construction machinery to adapt to complex environmental conditions and foster a more favorable acoustic environment. This study involved collecting sound samples from a specific loader model under various operating conditions and conducting a spectrum analysis to determine the amplitude frequency range. The analysis entailed comparing the characteristic loudness in objective terms with the frequency band range of noise sources to pinpoint the primary contributors to noise. Additionally, the study explored sound quality characteristics through the variations in loudness and sharpness, two objective metrics. The findings indicated that: (a) under the conditions of driving forward, reversing, and cab lifting, the peak characteristic loudness values were concentrated between 0.9–3.0 Bark and 0.2–1.8 Bark, respectively, with average loudness values for the left and right ears being 58.9 sone and 55.8 sone. The average sharpness values for the left and right ears were 2.57 acum and 2.48 acum, respectively; (b) the main noise sources within the driver's cab were identified as the cab panels and the engine's fundamental frequency, while external noise primarily emanated from the engine intake, exhaust, and the cooling fan; (c) loudness and sharpness values were higher during acceleration both forward and backward, and these values were also higher in the left ear than in the right during cab lifting. These conclusions provide a foundational and practical reference for future initiatives to enhance and optimize sound quality in high-end construction machinery.**

Index Terms—**Construction machinery, Noise, Experimental, Sound quality**

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I. INTRODUCTION

The development of high-quality construction machinery significantly impacts China's economic growth. This advancement has raised expectations regarding the comfort and quality of such equipment. One prominent issue is the high noise levels and suboptimal working conditions, which have emphasized the need for sound quality evaluation in construction machinery [1-2]. Recent research has revealed deficiencies in the traditional A-weighted sound pressure level evaluation method, which fails to accurately reflect subjective perceptions and does not consider the spectral characteristics of sound. These shortcomings underline the urgent necessity for developing objective sound quality evaluation standards [3-4].

In recent years, there has been a marked increase in research dedicated to the objective evaluation of sound quality. Studies indicate that loudness and sharpness are critical factors, accounting for more than 50% of the objective sound quality (SQ) evaluation and are used in over 70% of evaluations concerning stationary vehicle noise [5]. Yang et al. demonstrated that loudness, sharpness, roughness, and A-weighted sound pressure levels play significant roles in differentiating automobile interior noise across various operating conditions, prompting recommendations for structural enhancements to improve sound quality [6]. Hao et al. analyzed in-vehicle noise signals of electric vehicles under steady conditions to pinpoint crucial physical acoustic and psychoacoustic parameters that significantly influence a simplified objective evaluation model of in-vehicle sound quality [7]. Lee et al. devised a method for predicting sound quality in car cabins by altering the acoustic properties of absorption materials, with the method's effectiveness verified through real-vehicle testing [8]. Zhang et al. examined the acceleration sound quality characteristics of a commercial vehicle under different torques and speeds, finding that both loudness and sharpness increased with speed, with loudness exceeding 100 sone and sharpness reaching over 2.1 acum at maximum speed [9].

This study involves experimental testing on noise near the driver's ears and external noise of a specific loader model under actual working conditions. We identified the primary noise sources through noise spectrum analysis under various working scenarios and conducted a psychological analysis of the sound quality characteristics of the test samples.

II. THE THEORETICAL BASIS OF SOUND QUALITY

Psychoacoustics studies the relationship between sound and the auditory perceptions it evokes [10], providing a theoretical framework for sound quality analysis [11]. As sound evaluation methodologies have evolved, the inadequacies of traditional A-weighting in capturing auditory perception have been increasingly addressed. In the 1990s, Blauer introduced the concept of sound quality, defining it as the appropriateness of sound within specific technical objectives or contextual tasks [12].

A. Masking Effect and Critical Bands

The masking effect, a core principle in psychoacoustics, describes how the perception of a quieter sound (the masked sound) is influenced by a louder sound (the masking sound). To more accurately simulate the filtering function of the cochlea in noise assessments, researchers adopted the term "critical bands" in psychoacoustic studies [13-14]. These bands, which reflect the filtering characteristics of the human ear's basilar membrane, divide the frequency range from 20 Hz to 16 kHz into 24 critical bands [15]. The correspondence between the critical band rate and frequency is shown as follows:

$$z = 13\arctan(0.76\frac{f}{1000}) + 3.5\arctan(\frac{f}{7500})^2 \quad (1)$$

where z represents the critical band rate, measured in *Bark*; f signifies the frequency; The relationship between critical bands and frequency is denoted by the critical band rate.

B. Objective Evaluation of Sound Quality

The objective evaluation of sound quality effectively quantifies subjective perceptions into measurable terms. This form of evaluation not only corroborates subjective assessments but also complements traditional methods such as A-weighted sound pressure levels [16].

Loudness is a pivotal factor in the objective evaluation of sound quality, primarily reflecting sound intensity. It is denoted by N and measured in *sone*. For example, a pure tone at 1000 Hz and 40 dB is established as 1 *sone*. Increasing loudness tends to elevate auditory interference, generally leading to a degradation in sound quality [17-18]. The calculation of loudness is expressed as:

$$N' = 0.08(\frac{E_{TQ}}{E_0})^{0.23}[(0.5 + 0.5\frac{E}{E_{TQ}})^{0.23} - 1](\frac{sone}{Bark}) \quad (2)$$

$$N = \int_0^{24Bark} N'(z)dz \quad (3)$$

where $N'(z)$ represents the characteristic loudness; E_{TQ} is the excitation at the hearing threshold under quiet conditions; E_0 is the excitation level when the reference sound intensity I_0 is $10^{-12}(W/m^2)$; N is the total loudness in sones; and z is the *Bark* value of the critical band, with *Bark* being a frequency scale based on critical bands.

Sharpness, on the other hand, addresses the timbre aspect of sound quality. By evaluating sounds characterized as sharp or dull, the harshness of the sound is determined. A higher sharpness value indicates a sharper sound and typically a poorer sound quality. Sharpness is quantified in *acum*, with 1 *acum* corresponding to a center frequency of 1 kHz and a bandwidth of 160 *Hz* [19-20]. The formula for sharpness is given by:

$$S = k\frac{\int_0^{24Bark} N'(z)\cdot z\cdot g(z)dz}{\int_0^{24Bark} N'(z)dz} \quad (4)$$

$$g(z) = \begin{cases} 1 & , z \le 16 \\ 0.06e^{0.1755z} & , z > 16 \end{cases} \quad (5)$$

where S represents sharpness; N signifies the overall loudness; $k=0.11$ is the weighting coefficient; z stands for the critical band's *Bark* value; $N'(z)$ denotes the characteristic loudness within the Bark domain; and $g(z)$ represents the loudness weighting function.

III. Sound Quality Experiment

A. Experimental Preparation

Preparation of Test Samples: The focus of this experiment is on the noise both inside the cabin and outside a specific domestic loader model under predetermined conditions. To ensure the authenticity and utility of the test results, sample collection was carried out in relatively open areas that mimic practical working environments. Sound signals were captured from both the driver's cabin and the exterior of the loader under various operational conditions.

Preparation of Experimental Instruments: The equipment used in this experiment includes a designated loader model, vibration acceleration sensors, 1/2-inch free-field microphon es, 1/4-inch pressure-field microphones, an LMS Test.Lab da ta acquisition system, a laptop equipped with a noise analysi s system, various connecting cables, and Origin data processi ng software.

B. Experimental Method

The experimental approach utilized LMS noise and vibrati on collection equipment, conforming to standards such as IS O 6394:2008 "Earth-moving Machinery—Determination of Emission Sound Pressure Level at Operator's Position—Stati onary Test Conditions", ISO 9249: 2007 "Earth-moving Mac hinery—Test Code for Net Power of Engines", ISO 6396: 20 08 " Earth-moving Machinery—Determination of Emission Sound Pressure Level at Operator's Position—Dynamic Test Conditions", and ISO 6393: 2008 " Earth-moving Machinery —Determination of Sound Power Level—Stationary Test Co nditions". To ensure the reliability of the test results, measur ements were taken at least three times, with 10-second test sa mples being chosen.

The arrangement for noise signal collection involved measurements both inside the cabin and outside the machine. The microphone positioned beside the driver’s ear inside the cabin was set 200 mm ± 20 mm from the mid-point plane of the driver’s head, placed on both the left and right sides. The layout for noise signal collection outside the loader, as depicted in Figure 1, includes three measurement positions. The x-axis represents the lateral distance from the measurement points, aligning with the direction of the loader's travel. The y-axis denotes the longitudinal distance from the measurement points, and the z-axis indicates their vertical height. The distance between measurement point 2 and the test vehicle is 15.84 m, while measurement points 1 and 3 are both 11.2 m from the vehicle. The spacing between these three points is consistently 11.2 m, and they are positioned 1.5 m above the ground.

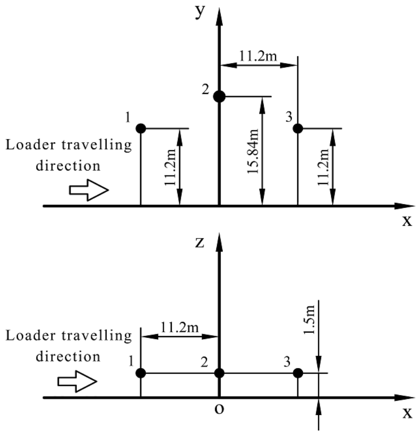


Figure 1 Off-board noise signal acquisition arrangement

C. Experimental Procedure

Initially, the entire vehicle was outfitted with sensors and microphones, targeting not only the driver's ear in the cab but also the floor and roof areas. Sensors were also strategically placed on components prone to vibration, such as the glass, steering pump, and suspension. To simulate the real-life operating conditions of the loader, various operational scenarios were enacted. The sound quality characteristics were then analyzed through spectral analysis of the collected data, leading to the generation of various objective evaluation curves. The experimental procedure is outlined in Figure 2. The marked portion of figure showed the microphone and sensor positions.

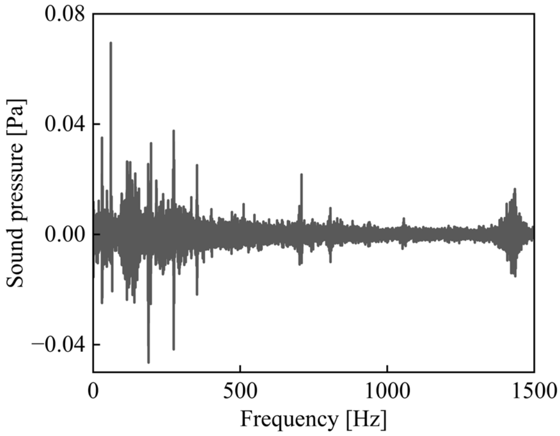
IV. Sound Quality Characteristics Analysis

This section presents a detailed analysis of peak sound pressure levels and main vibration frequency bands through spectral analysis of test signals. Objective sound quality parameters are used to identify principal noise sources under various operating conditions and to examine the variation patterns of these parameters.

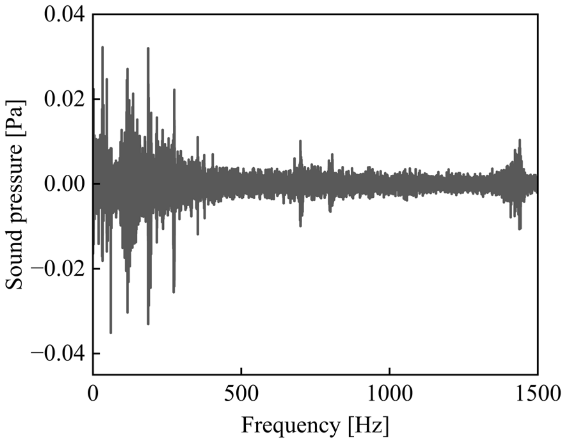
A. Noise Spectrum Analysis under Different Working Conditions

Figure 2 Loader condition test procedure

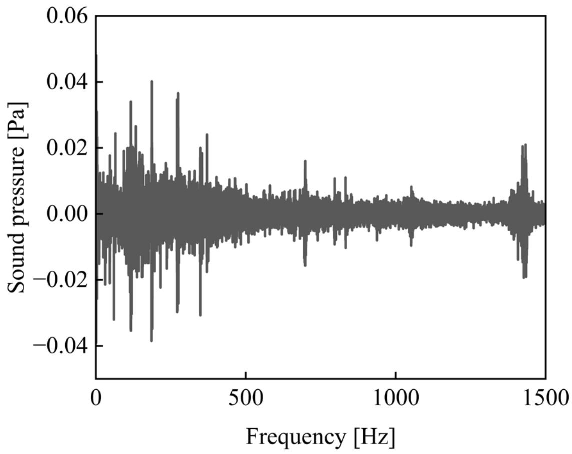
Figure 3 illustrates the main frequencies and amplitudes from three external measurement points on the machine while operating in first gear forward. As the engine speed increases, fluctuations become noticeable in the frequency domain graphs of these points, with amplitude regions predominantly concentrated below 300Hz. At these points, the lowest recorded frequency is 30.85Hz with a sound pressure of 0.04Pa, and the highest is 1447.08Hz with a sound pressure of 0.02Pa. Frequencies peak around 1400Hz, while the lowest frequencies are around 30Hz.



(a) Frequency amplitude of measurement point 1

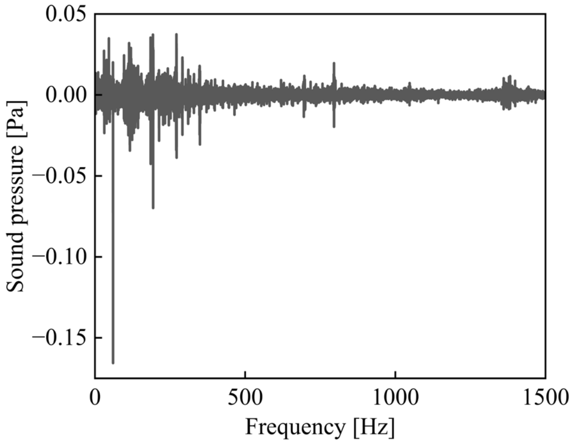


(b) Frequency amplitude of measurement point 2

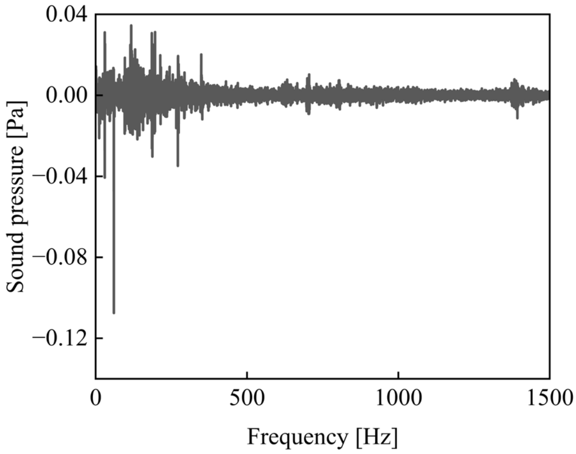


(c) Frequency amplitude of measurement point 3
Figure 3 Frequency amplitude of first gear forward working condition

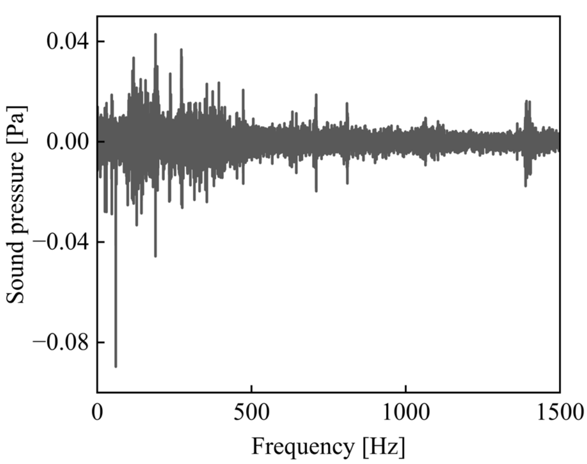
In the first gear reverse operating condition, Figure 4 shows the main frequencies and amplitudes at the same three measurement points. The lowest frequency is 28.99Hz with a sound pressure of 0.7Pa, and the highest is 1392.34Hz with a sound pressure of 0.01Pa. The highest frequencies cluster around 1380Hz, with the lowest frequencies near 29Hz.



(a) Frequency amplitude of measurement point 1

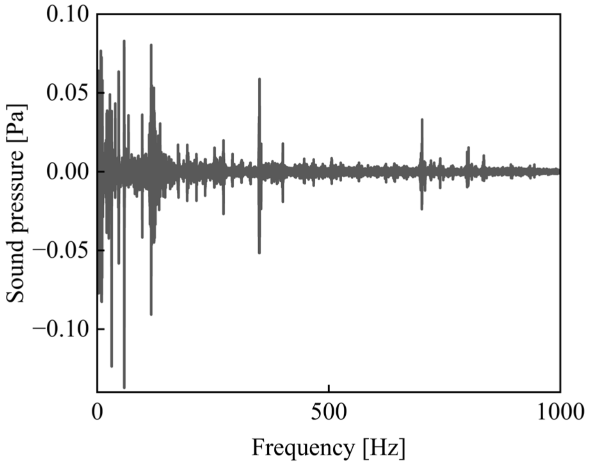


(b) Frequency amplitude of measurement point 2

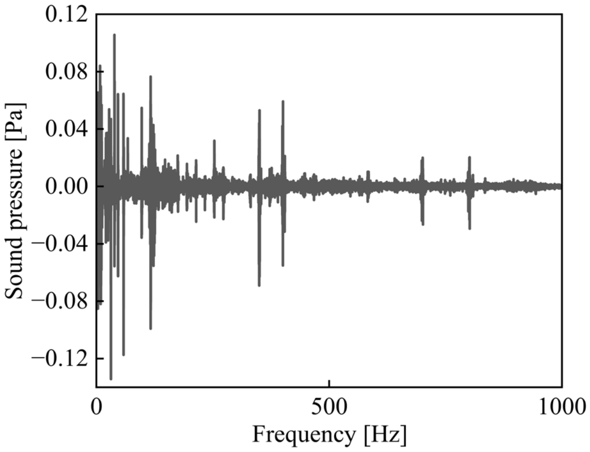


(c) Frequency amplitude of measurement point 3
Figure 4 Frequency amplitude of first gear backward condition

Figure 5 displays the main frequencies and amplitudes of noise adjacent to the driver's left ear during the lifting condition of the working device. The lowest frequency among these measurement points is 30.40Hz with a sound pressure of 0.063Pa, and the highest is 802.78Hz with a sound pressure of 0.026Pa. Within the cabin, the highest noise frequency is notably lower, while the lowest frequency is relatively higher.



(a) Frequency amplitude at the left ear



(b) Frequency amplitude at the right ear

Figure 5 Frequency amplitude of noise in the driver's compartment under work unit lifting condition

Based on amplitude statistics from experimental samples, Table 1 presents the main vibration frequency bands. By comparing the frequency range extracted from these samples with the natural frequencies of various loader components, preliminary noise sources are identified. This comparison assists in subsequent analyses of objective evaluation results for sound quality.

TABLE I
MAIN VIBRATION FREQUENCY BANDS

Serial Number	Frequency Range (Hz)
1	29.77~33.11
2	38.34~40.05
3	58.01~59.81
4	112.83~118.41
5	186.66~197.78
6	271.79~275.96
7	349.16~354.61
8	1392.34~1447.08

B. Characteristics of Sound Quality under Different Operating Conditions

The analysis of sound quality characteristics employs psychological objective parameters to investigate noise characteristics under varied operating conditions. Prominent peaks and frequency bands are identified. By utilizing characteristics such as loudness and sharpness curves, and referencing the table of natural frequencies of various loader components under actual working conditions (shown in Table 2), main noise sources within different frequency ranges are determined. Additionally, an analysis is conducted on the curve characteristics of the objective parameters of loudness and sharpness.

TABLE II
CORRESPONDING FREQUENCY OF EACH COMPONENT NOISE SOURCE

Noise Sources	Frequency (Hz)
Driver's compartment panels	31
	40
	60
Intake noise	117
Exhaust noise	117
Cooling Fan	93.75~280
Six-cylinder/engine	39~117
Generator	227.27~678.79
Air Conditioning	373.3
Steering pump	351
Work pump	401.31

1. Analysis of Characteristic Loudness

Characteristic loudness refers to the loudness within a specific frequency band and represents the distribution density of loudness. By analyzing the characteristic loudness curve and spectrogram, it is possible to ascertain the sound characteristics under various working conditions and identify the corresponding noise sources.

First Gear forward Operating Condition

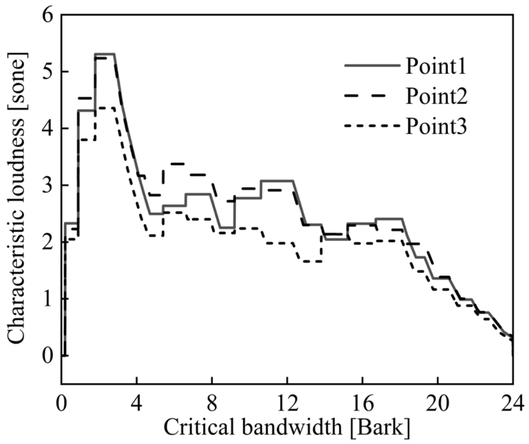
Figure 6(a) displays the characteristic loudness at three measurement points under the first gear forward operating condition. The primary loudness peaks are observed within the range of 0.9 to 2.8 Bark, corresponding to a frequency range of 90 to 280Hz, where loudness levels vary from 3.8 to 5.4 sone. A comparison with the frequency domain graph indicates that the amplitude ranges in the frequency domain closely align with the critical band range of these loudness peaks. The noise in this frequency band primarily emanates from the intake and exhaust systems, as well as from cooling fan noise. Loudness levels in other frequency bands generally remain below 3.5 sone, with the characteristic loudness curve demonstrating a decreasing trend beyond the peak, tapering off smoothly and inconspicuously.

Reverse Operating Condition

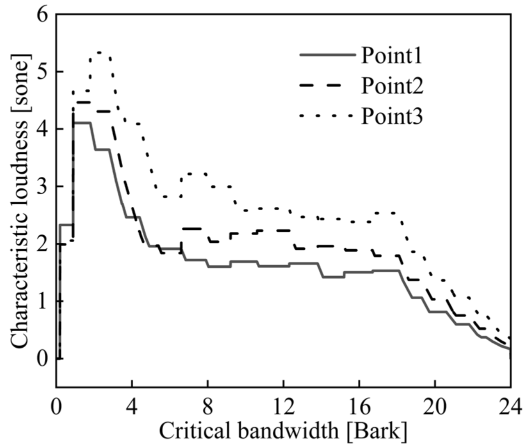
Figure 6(b) illustrates the characteristic loudness under the reverse operating condition. Here, the primary loudness peaks range from 0.9 to 3.0 Bark, correlating to a frequency range of 90 to 300Hz, with loudness peaks between 4.0 to 5.4 sone. Notably, the curve for measurement point 3 is significantly higher than for the other two points. Analysis of actual working conditions and the natural frequencies of various loader components indicates that the predominant noise sources in this band are again intake and exhaust noise, along with cooling fan noise. Other frequency bands typically exhibit loudness values below 3.5 sone, and the loudness curve similarly shows a decreasing trend after reaching its peak.

Noise at Driver's Ears during Empty Lifting Condition

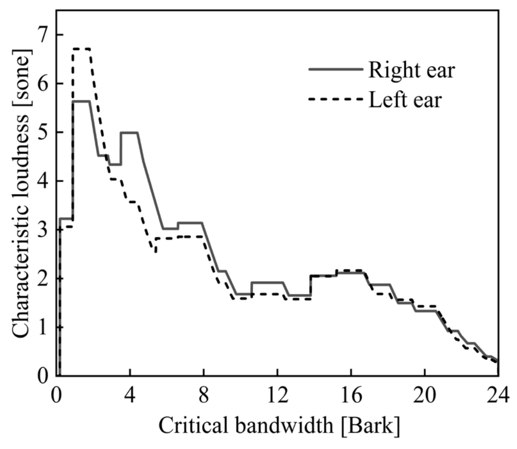
The characteristic loudness of vibration noise experienced by the driver at the left and right ears during the empty lifting condition is depicted in Figure 6(c). The main loudness peaks are concentrated within the ranges of 0.2 to 0.9 Bark and 0.9 to 1.8 Bark. When compared with the frequency domain graph for this condition, the amplitude ranges in the frequency domain closely match the critical band ranges of these loudness peaks, corresponding to frequency ranges of 20 to 90Hz and 90 to 180Hz, with loudness peaks between 5.5 to 6.7 sone. Compared to external noise, the vibration frequency bands generated by the cabin panels are more pronounced. The primary sources of noise in these peak frequency bands include the engine's fundamental frequency, cabin panels, and the cooling fan. Notably, the characteristic loudness peak for the left ear is higher than that for the right ear, although the average characteristic loudness for the right ear exceeds that of the left.



(a) First gear forward curve



(b) First gear backward curve



(c) By-ear noise curve for lifting conditions

Figure 6 Characteristic loudness graph

2. Loudness Analysis

As illustrated in Figure 7(a), during the forward operating condition of the loader, the loudness profile across measurement points 1, 2, and 3 is characterized by an initial increase followed by a subsequent decrease. Specifically, the loudness curve at measurement point 1 exhibits an upward trend, peaking at 67 sone. At measurement point 2, the curve remains relatively stable with an average loudness of 48 sone. At measurement point 3, a notable downward trend is observed, with loudness decreasing from 66 sone to 49 sone. The sound quality at measurement point 2 is considered superior due to its stability, in contrast to the fluctuating loudness at points 1 and 3, which correlate with the beginning and end of acceleration, respectively.

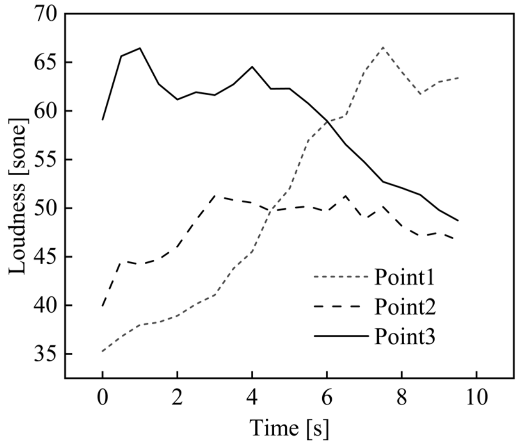
Figure 7(b) reveals that under the reverse operating condition, as the loader progresses sequentially through measurement points 1, 2, and 3, the loudness curves similarly exhibit an initial increase followed by a decrease. Overall loudness values are lower than those observed in the forward condition. The curve for measurement point 1 shows an upward trend, peaking at 65.9 sone, while measurement point 2 remains relatively stable with an average loudness of 49.1 sone. The curve at measurement point 3 decreases from a peak of 63 sone to 38 sone. This fluctuation in loudness at points 1 and 3 corresponds to the phases of initiating and concluding acceleration in reverse, leading to significant loudness variability. Additionally, the irregular and complex road conditions encountered by mining dump trucks often result in inconsistent ground contact, typically limiting the dynamic deflection of tires to one-third of the static tire load.

As depicted in Figure 7(c), during the operation of lifting the working device, the loudness at the left ear consistently exceeds that at the right ear, peaking at 63.8 sone at 9.5 seconds. The loudness curves for both ears remain relatively stable, averaging 59.1 sone at the left ear and 55.4 sone at the right ear. The sound quality at the left ear is slightly inferior, likely due to its proximity to the loader's door, which exposes it to more external noise and engine excitation.

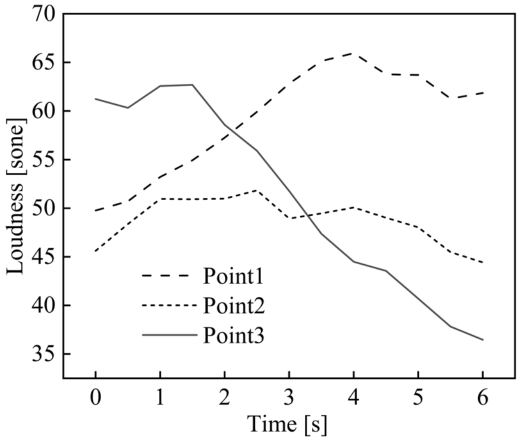
Loudness serves as a primary objective indicator of engine sound quality. At the same time, it is especially noticeable both inside and outside the cab. Clearly, under various operating conditions, loudness significantly influences the perceived sound quality during acceleration and deceleration phases. While higher loudness levels typically indicate poorer sound quality, lower loudness levels show favorable sound quality, they are not the sole determinant of overall sound quality.

3. Sharpness Analysis

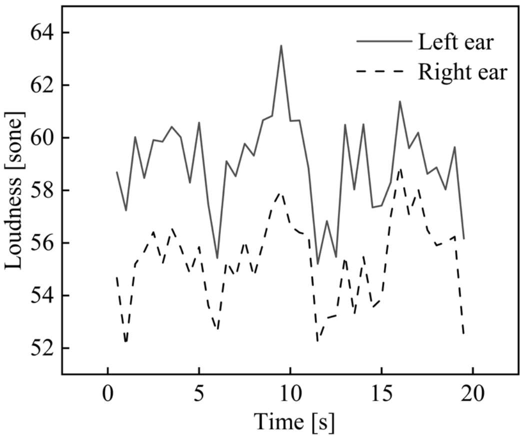
As depicted in Figure 8(a), under the first gear forward condition, the sharpness curves at measurement points 1 and 2 exhibit an upward trend, indicating an increase in sharpness, while the curve at measurement point 3 shows a downward trend. Generally, the sharpness curves demonstrate a pattern of initial increase followed by a decrease. The average sharpness at point 1 is 1.33 acum, while at points 2 and 3, the averages are both 1.39 acum. During acceleration, as the loader's speed increases, the high-frequency noise components become more pronounced, which are subjectively perceived as more piercing and result in a degradation of sound quality.



(a) First gear forward curve



(b) First gear backward curve

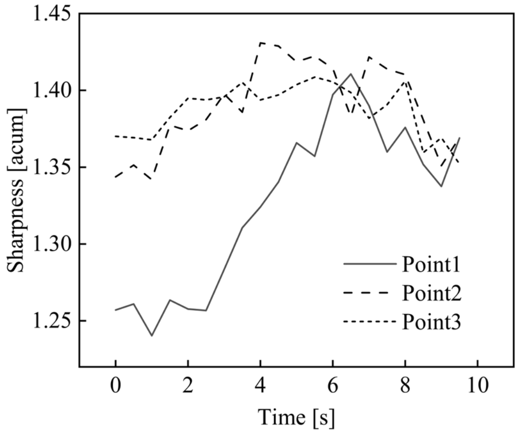


(c) By-ear noise curve for lifting conditions
Figure 7 Loudness graph

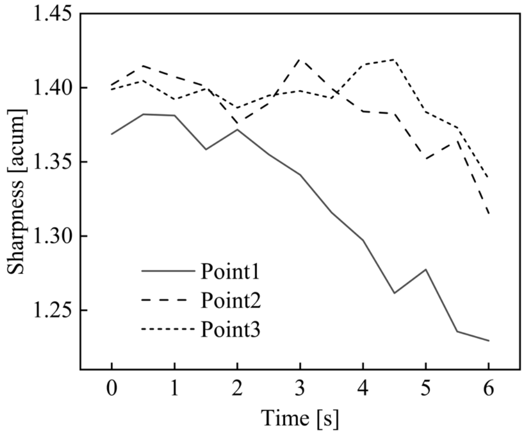
As illustrated in Figure 8(b), under the reverse gear condition, the sharpness curves uniformly exhibit a decreasing trend. Consistent with the forward operating condition, the average sharpness value at point 1 is 1.33 acum, the lowest among the measurement points, with points 2 and 3 recording averages of 1.39 acum and 1.40 acum, respectively. During reverse operation, as the engine speed increases, sharpness also increases, leading to diminished sound quality.

Figure 8(c) reveals that during the lifting operation of the working device, the sharpness value at the left ear inside the cab is significantly higher than that at the right ear. The average sharpness values during this operation are 1.29 acum for the left ear and 1.26 acum for the right ear. The cab door, located on the left side, along with vibrations generated by engine excitation and cabin panels, contribute to better sound quality at the right ear compared to the left.

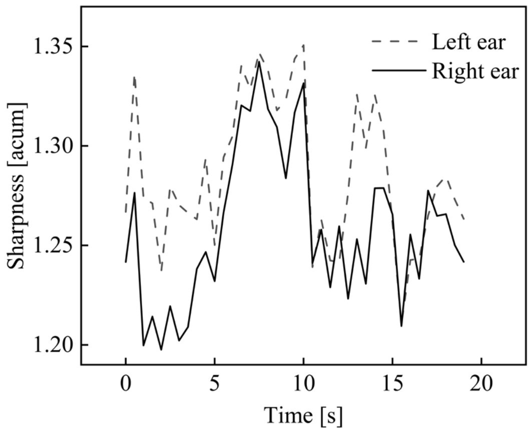
Sharpness, in contrast to loudness, focuses more on the high-frequency components of sound. Variations in vehicle speed and the pronounced high-frequency noises generated during the lifting operation lead to a sharper, more piercing subjective perception and, consequently, poorer sound quality.



(a) First gear forward curve



(b) First gear backward curve



(c) By-ear noise curve for lifting conditions
Figure 8 Sharpness graph

V. CONCLUSIONS

This study investigates the sound quality characteristics of a specific type of loader by collecting external and indoor noise under three distinct test conditions—forward, backward, and during the operation of the lifting device. Main noise sources were identified using time-frequency analysis. The study also measured changes in objective sound quality parameters (characteristic loudness, loudness, and sharpness) under different operational conditions, leading to the following conclusions:

(1) Comparative analysis of spectrograms and the characteristic loudness revealed that the main vibration frequency bands outside the machine are concentrated in the range of 93.75 to 280 Hz. Inside the cabin, the predominant vibration frequency bands range from 20 to 90 Hz and 90 to 180 Hz. The primary sources of external noise include the engine's air intake and exhaust systems, alongside the cooling fan. Internally, noise predominantly emanates from the engine's fundamental frequencies, the compartment's panels, and the cooling fan.

(2) During the loader's forward and reverse driving conditions, the curves of loudness and sharpness—two objective parameters—show significant fluctuations with the increase in engine speed. The peak values of loudness and sharpness reached 67 sone and 1.43 acum, respectively. In the lifting operation, as the bucket rises, the loudness at the left ear in the cab is significantly higher than at the right ear, with the sharpness at the left ear also slightly exceeding that of the right ear. Consequently, the sound quality at the right ear inside the cab is superior to that at the left ear, and the sound quality of external noise deteriorates rapidly with the increase in vehicle speed.

(3) The use of characteristic loudness, loudness, and sharpness as objective evaluation indices of sound quality can effectively describe the noise characteristics of the loader under different working conditions. The increase in engine speed and the vibration generated by the compartment panels will lead to the deterioration of sound quality. Future research will focus on the theoretical analysis and multi-objective optimization of sound quality, based on experimental data, as well as on prototype trial production to enhance the sound quality characteristics of this type of equipment.

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(1) Zhanlong Li, Shixun Zhao, Bao Sun, et al. "Performance and Optimization of the Hydropneumatic Suspension of High-Speed Wheeled Excavators" Engineering Letters, vol. 31, no.2, pp674-680, 2023.
(2) Zhanlong Li, Zheng Zhang, Zhizhao Ren, et al. "Research on damage behavior of silicone rubber under dynamic impact" International Journal of Non-Linear Mechanics, vol. 164, no.104775 ,2024.
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Modification Instructions

1） We have changed the revision date to December 1， 2024.

2） We have corrected the error in the first author's unit name.We have changed Taiyuan University of Science to Taiyuan University of Science and Technology.