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PSYCHOACOUSTIC INVESTIGATION OF THE SOUND RADIATION OF ROTARY DRILLING RIGS

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ABSTRACT

The acoustic emission of rotary drilling rigs consists of the partial sound sources of the diesel engine, the fans of the cooling system and the rotary drive. Usually, the machines are acoustically characterised according to the outdoor noise directive 2000/14/EC with a value for the averaged sound power. However, the subjective noise exposure for construction site employees can differ from the measured sound power level depending on their location on the construction site. In our test setup, we examine the acoustic emission of the device from the perspective of the construction site workers, once from the machine operator in the operator's cab and once from the site assistant giving instructions outside. Using artificial head measurements, we analyse the psychoacoustic parameters of loudness, sharpness, roughness and tonality at different operating points of the drilling rig. It turns out that, despite similar values for the sound power, the psychoacoustic parameters can characterise the sound radiation of the drilling rig in a more differentiated way at specific operating points.

Keywords: *psychoacoustics, construction site noise, rotary drilling rigs*

1. INTRODUCTION

According to a report by the German Federal Ministry of Labour and Social Affairs, noise-induced hearing loss is the second most common recognised work-related disease in Germany. In 2023, 18,076 new cases of occupational noise-induced hearing loss were reported to the relevant accident insurance companies. Of these, 7,889 new cases have already been confirmed and in 283 cases, noise-induced hearing loss was the reason for early retirement [1]. A significant proportion of these cases affect employees in the construction industry, with around 1,500 new cases of noise-induced hearing loss being recognised in this sector each year [2].

Particularly on major construction and civil engineering sites, construction workers and residents are exposed to high noise emissions due to the heavy construction machinery used. One machine type frequently employed in this context are rotary drilling rigs, which are used to drill piles, carry out soil mixing procedures or prepare the ground for following process steps [3]. An example of such a machine is shown in Fig 1.

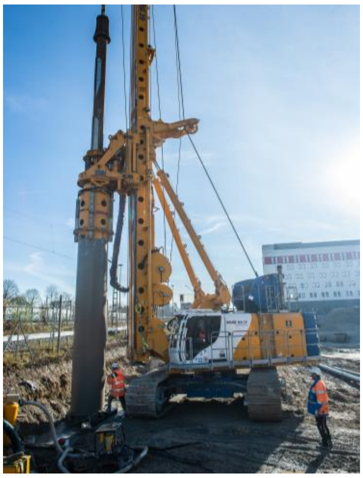

Figure 1. Example for a rotary drilling rig.

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2. PSYCHOACOUSTIC PARAMETERS

The application of psychoacoustic methods for product optimisation is nowadays well established in the mobility sector. Some examples in this context are the characterisation of automotive HVAC noise [4], sound design of warning signals for electric cars [5], or the characterisation of motors in pedelecs [6]. We apply the software ArtemiS SUITE 16.0 from HEAD acoustics to calculate the psychoacoustic parameters mentioned below.

2.1 A-weighted sound pressure/power level

For practical applications, the A-weighted sound power level is a commonly used metric to quantify the acoustic emission of a machine. The A-weighting takes into account the fact that the human ear is less sensitive to particularly low and high frequencies. However, strictly speaking, the A-weighting filter only corresponds to the curve of equally loud perceived tones at a volume between approximately 20 and 40 phon. Nevertheless, A-weighting is a very good approximation for the evaluation of tones, narrow-band noise and simple A-B comparisons, where A and B have the same sound characteristics. For broadband noise and when comparing noises that differ greatly in their underlying characteristics (e.g. additional tonal components), pure A-weighting however underestimates the volume compared to subjective volume perceptions from listening tests [7].

2.2 Loudness

When assessing the volume of a noise signal, loudness takes into account the physiological characteristics of human hearing. This includes, among other things, taking into account frequency-dependent masking effects and incorporating different rating curves depending on the maximum sound pressure level being present [7]. A 1 kHz sinusoidal tone with a sound pressure level of 40 dB is assigned the unit 1 *sone*. In our investigations, we use the calculation of loudness according to DIN 45631/A1, which is based on the frequency group method according to ZWICKER.

2.3 Sharpness

Speaking figuratively, sharpness describes the location of the centroid of the loudness-corrected spectrum of a sound. Noises with a focus in the high-frequency sound range are perceived as sharper [7]. A narrowband noise around the centre frequency of 1 kHz with the width of one critical band and a sound pressure level of 60 dB corresponds to 1 *acum*. In the present case, we use the calculation model according to AURES with an underlying loudness calculation according to DIN 45631/A1.

2.4 Roughness

The roughness indicates a parameter for characterising frequency- and amplitude-modulated sounds. A 1 kHz sine tone at 60 dB, which is amplitude-modulated with a frequency of 70 Hz and a modulation degree of 1, corresponds to a roughness of 1 *asper* [8]. We use the procedure according to DIN 38455 to calculate roughness.

2.5 Tonality

The tonality parameter is used to rate noise in terms of the annoyance of specific tonal components it contains. We use the tonality according to the SOTTEK hearing model, as shown in ECMA 418-2, in our analyses. A 1 kHz tone with a level of 40 dB receives the unit 1 tu_{HMS} (tonality units according to the hearing model of Sottek). Compared to other methods of calculating tonality, such as the tone-to-noise ratio or DIN 45681, the metric used here has the advantage that it uses psychoacoustic loudness as the basis for its calculations [9].

3. MEASUREMENT SET-UP

Construction equipment and machinery used outdoors are sound-characterised in Europe in accordance with the outdoor directive 2000/14/EG. This directive refers to EN ISO 3744 for determining the sound power of rotary drilling rigs. Accordingly, the sound power of rotary drilling rigs is determined using an enveloping surface method for a free sound field above one reflecting surface Fig. 2 shows the measurement set-up in this case. 12 microphone positions are defined around the device in a hemisphere with a radius of 16 m, in line with the standard. The microphones used for the sound power measurement are ½”- free-field microphones of the type MK 255 from MTG.

We use the KEMAR Head & Torso 45BB-10 with anthropometric ears as the artificial head. The artificial head is placed at a distance of 4 m from the outer contour of the machine, which is a typical working position for the drilling assistant (see Fig. 1). Data acquisition is carried out with an SQuadriga II from HEAD acoustics. During the measurements, the machine operator inside the device wears the Mobile Headset BHS II together with the mobile recorder SQobold from HEAD acoustics.

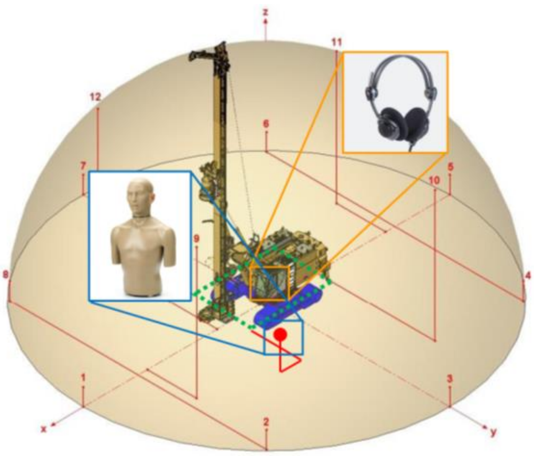

Figure 2. Set-up for determining the sound power of a rotary drilling rig according to EN ISO 3744. Also highlighted is the measurement equipment for the binaural recordings at the related positions

In our tests, we analyse a medium-powered rotary drilling rig with a 6-cylinder 4-stroke diesel engine. As already mentioned, the main sources of noise on such a machine are the diesel engine itself, the fans for cooling the engine, hydraulic circuit and charge air, and the operation of the power rotary head. In our measurement programme, we analyse the device in four different operating modes, which are summarised in Tab. 1. We examine time periods of 15 s for each operating point.

Table 1. Test plan of the considered operating points of the rotary drilling rig with corresponding sound power levels according to EN ISO 3744.

#	engine speed	fan speed	rotary drive	sound power level
M000	85 %	70 %	off	$L_{w,min}$
M100	100 %	70 %	off	$L_{w,min}$ +0,7dB(A)
M010	85 %	100 %	off	$L_{w,min}$ +7,5dB(A)
M011	85 %	100 %	on	$L_{w,min}$ +8,3dB(A)

In the first operating condition, M000, the engine is running at 85% of its nominal speed. All the fans are manually controlled at 70% of their maximum speed and the rotary drive is not in operation. In this setting, the lowest of all sound power levels, $L_{w,min}$, is measured and used as a reference for the other operating conditions. In the second operating state, M100, the speed of the diesel engine is then increased to nominal speed (100%). This results in a sound power increased by 0.7 dB(A) compared to the initial variant. In the third operating state, M010, the engine speed is reduced again to 85% of the nominal engine speed and the speed of the fans is increased to 100% instead; the rotary drive remains switched off. Compared to the initial variant M000, a sound power level increased by 7.5 dB(A) is now measured. In the last set-up, M011, the rotary drive is switched on, the motor engine speed remains at 85 % of its maximum and the speed of the fans are operated at 100 %. This results in an 8.3 dB(A) increase in sound power compared to the initial variant.

4. RESULTS

In Fig. 3, the results of the psychoacoustic analysis at the four different operating points are shown with the help of bar charts. Each row of the subplot represents a separate metric. Starting with level in dB(A) and moving on to loudness, sharpness, roughness and tonality. The results for the operator's position are shown in orange bars, and the results for the assistant are shown in blue.

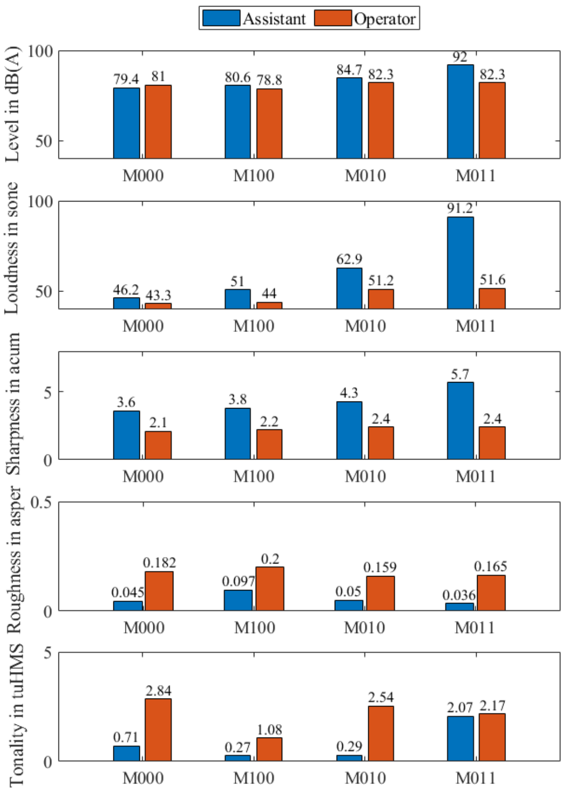

Figure 3. Single value results for the five different metrics of the psychoacoustic analysis.

4.1 Increased diesel engine speed

First, we investigate how an increase in engine speed (M000->M100) affects the sound perception for the operator and the assistant. According to Tab.1, this change results in a minimal increase in sound power of 0.7 dB(A). At the assistant's position, a slight increase in loudness of 4.8 sone is measured. While the pure A-weighted sound pressure level at the operator's position decreases by 2.2 dB(A) for this setting, the loudness increases by 0.7 sone. When listening to the sound recordings of the two operating points at the two positions, it becomes clear that the increase in engine speed is most clearly described by the parameters roughness and tonality. For both the operator and the assistant, the increase in engine speed results in a significant increase in the parameter roughness. At the same time, the parameter tonality decreases strongly at both observer positions.

4.2 Increased fan speed

Subsequently, we analyse how an increase in the fan speed (M000->M010) affects the sound perception of the construction site workers. With this particular modification, an increase of 7.5 dB(A) was observed for the sound power in Tab.1. In this case, an increase in loudness of 7.9 sone can be measured for the operator, and for the worker in front of the drilling rig, the increase is 16.7 sone. In addition to the volume, the sensation of sharpness changes when the fan speed is increased. The tonal components of the secondary aggregates are suppressed by the noise of the fan, which is expressed in the tonality parameter.

4.3 Switching on the rotary drive

Finally, we consider how an additional switch-on of the rotary drive (M010->M011) affects the noise perception of the construction site workers. The sound power level changes by only 0.8dB(A) at this setting. From the operator's position, it is almost impossible to detect the switching on of the rotary drive acoustically. However, the most significant differences for the assistant in the whole measurement campaign arise with this variation. The loudness increases in this case by 28.3 sone. The measured sharpness changes from 4.3 to 5.7 acum. And the tonality for the assistant increases by 1.78 tu_{HMS}.

5. CONCLUSION

In the present study, we examined how a change in characteristic machine parameters of a rotary drilling rig affects the subjective sound perception of construction site employees. Due to the fact that the machine emits a broadband noise spectrum with many different partial sound sources, the measured sound power level does not always adequately reflect the perceived noise exposure at the positions of the construction workers. Our research showed that the assistant perceives the various operating states of the machine in a much more differentiated way than the machine operator. This indicates that the machine's cab provides sound insulation and shields the operator. The work carried out shows that the psychoacoustic parameters are suitable for assessing the subjective noise exposure of construction workers.

6. ACKNOWLEDGMENTS

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