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PSYCHOMETRIC PROCEDURES FOR MEASUREMENTS OF EQUAL LOUDNESS LEVEL CONTOURS

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1. INTRODUCTION

Knowledge of human hearing sensitivity and loudness perception is essential in a number of applications within noise assessment and audiology. At present, data on binaural loudness perception of pure tones in a free field are given in the standard ISO 226 of 1987 [1]. For the frequency range 20-12500 Hz this standard covers minimum audible field and equal loudness level contours in the level range up to 100 phon. ISO 226 is based on experimental data made by Robinson and Dadson in 1956 [2]. However, a number of later experiments [3,4,5,6,7] have not been able to reproduce the equal loudness level contours given in ISO 226, nor to get comparable results from different laboratories. Fig. 1 shows the difference between ISO 226 and the mentioned later experiments for the 40 phon level. The standardized levels are significantly lower than what any other experiment has shown, especially at frequencies below 1 kHz. For a fixed frequency, e.g. 63 Hz, loudness levels can be plotted versus sound pressure levels as shown in Fig 2. Relatively larger deviations are found between the measured loudness levels than the hearing thresholds found in the lower left side of the curves. The working group ISO/TC43/WG1 has decided to make a revision of ISO 226. In order to get more consistently data from different laboratories a number of preferred test conditions have been specified for both threshold and loudness experiments [8]. As regards the free field hearing thresholds, which showed relatively good agreement, are now standardized in ISO 389-7. A similar work on loudness data is now in progress.

The aim of this experiment is to produce data for the standardization work, hence the preferred test conditions are followed strictly. In the final experiments free field hearing thresholds will be measured for 25 otological normal subjects at each of the 1/3 octave frequencies from 20 Hz to 20 kHz. Loudness level measurements are planed to include the frequencies below 1 kHz only, at levels ranging from 20 phon to 100 phon. In the following the psychometric method used for loudness level measurements are considered based on experiences from a methodology study of psychometric functions used for threshold measurements [9] and results from other investigations of equal loudness contours.

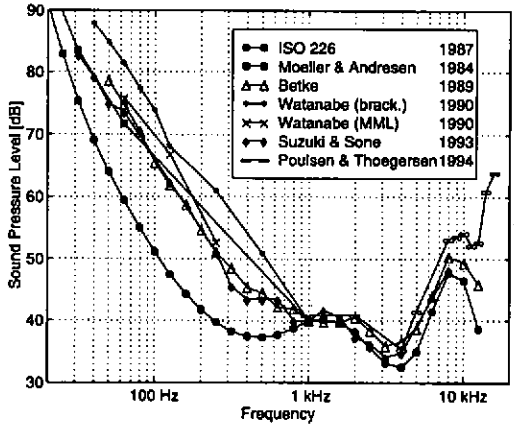

Figure 1: Equal Loudness data for 40 phon from ISO 226 and newer experiments.

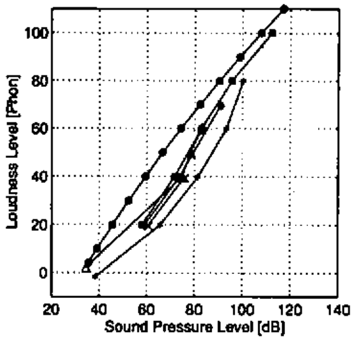

Figure 2: Equal loudness data for 63 Hz from ISO 226 and newer experiments. The use of symbols are similar to those used in Fig. 1.

For threshold measurements, the preferred test conditions specify the use of the ascending or the bracketing method as standardized in ISO 8253-1 [10]. We have previously found good agreement between results from these methods [9]. The methods were based on simple detection where the subject pressed a button if he/she was able to hear a presented tone. However, the preferred test conditions does not specify a psychometric function for loudness experiments except that it should be implemented as a 'Two Alternative Forced Choice' method. This is usually done by presenting pairs of tones for the subject separated by a short pause. One tone is the reference tone with fixed level and a frequency of 1 kHz, the other is the test tone with a different frequency and variable level. The test tone and the reference tone are presented in random order. The subject has to indicate by pressing a button which of the first or the second tone was perceived as the loudest. When the test tone and the reference tone are equally loud, the point of subjective equality (P.S.E.) is found.

2. LITERATURE STUDY

Usually the method of constant stimuli has been used as the psychometric method for loudness experiments. An experiment performed by Gabriel *et al.* [11] has shown that different intervals of stimuli levels used by a constant stimuli method can produce different P.S.E.'s. It was possible to reproduce data from two earlier german experiments with an internal difference exceeding 10 dB on a 30 phon curve. The results of Gabriel's experiment showed a bias on the P.S.E for the method towards the gravity point of the presentation level interval.

Only a few investigations have used an adaptive psychometric method for loudness measurements. Møller and Andresen [3] used the Method of Maximum Likelihood based on estimation of the mean value, μ and standard deviation, σ of the psychometric function. After each presentation of a tone pair a new estimate of μ and σ were calculated and the next stimulus was randomly chosen among the 5 levels: μ, $\mu\pm\sigma$ and $\mu\pm2\sigma$. The estimates of μ and σ were restricted to integer values and the method terminated when each of the 5 dynamic changing levels had been presented. Data from this experiment is mainly covering the infrasonic frequencies but for 31.5 Hz and 63 Hz they show a good agreement with other experiments.

Another experiment which has used an adaptive method is Watanabe [5]. Here a bracketing method is made with a step size of 2 dB. The first presentation level for the test tone was chosen 15-20 dB above the ISO 226 level and it was usually evaluated as the loudest tone. This started a descend. After each change in the responses during a descend (ascend) a jump of 4-5 dB were made in the same direction and an ascend (descend) was following. The data from Watanabe's work are in general placed at a higher sound pressure level than other data. Again a bias towards the gravity point of the presentation levels can be expected and give an explanation of the relative high levels of the P.S.E.'s. Watanabe also measured some loudness points with a method similar to the method used by Møller and Andresen. This gave lower values compared to the bracketing method, see Fig. 1.

3. METHOD

A system for hearing threshold and equal loudness level measurements in free field has been established in our laboratory. Before the main experiments of this work will be carried out, some pilot experiments are needed to test and improve the design of a psychometric method for equal loudness measurements. Based on the literature study an adaptive method is preferred. Two pilot experiments are planed with adaptive methods to examine the effect of the start point and to examine biasing effects in the method.

In the first pilot experiment 3 different methods will be tested at 50 phon, 100 Hz with start points at 40, 55, 70, 85 and 100 dB SPL for the test tone chosen in random order. A bracketing method very similar to the method used by Watanabe will be used together with a bracketing method using 5 dB step size. The latter using an interlacing of the levels to improve the resolution of the presented levels. The meth[illegible] minated after 6 ascends and descends. The third method [illegible] Method of Maximum Likelihood used by Møller and Andresen. To start this method some initial presentations are needed for the estimation of μ and σ, so an ascend and a descend with 10 dB steps are placed at first.

In the second pilot experiment the 50 phon level at 100 Hz is measured with the interlaced bracketing method. The start point is the ISO 226 level and the first ascend/descend is using 10 dB steps, the following 6 ascends-/descends are using 5 dB steps. One repetition is made. The individually measured P.S.E. at 100 Hz is next used as the reference tone to measure the P.S.E. at 1 kHz, to see whether it is possible to return to 50 dB. The idea is that if tone *A* is just as loud as tone *B* then *B* must be just as loud as *A*. Otherwise the method used to measure the point of equality is biased.

Preliminary results obtained until now supports the hypothesis of a bias towards the point of gravity of the presentation levels. Furthermore the start level of the test tone seems to influence the final result obtained by an adaptive psychometric method.

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SOUND QUALITY ASSESSMENT OF A DIESEL ENGINE DUE TO STRUCTURE MODIFICATIONS

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1. INTRODUCTION

Traffic noise is a predominant environmental problem in the modern society. Among the sources of traffic noise, the sound from heavy truck diesel engines has frequently been reported to cause annoyance. To minimise the disturbance a reduction in dB(A) might be insufficient, as "80 dB(A) trucks" can sound very different. To improve the situation it is necessary to correlate the acoustic signal with the annoyance response. Psychoacoustic research has resulted in a number of psychoacoustic (PA) descriptors, which can be related to the annoyance of vehicle sound [1,2,3], e.g. loudness, sharpness, roughness, tonality and impulsiveness.

Generally, a first step in product-sound-quality [4] evaluation is to define a target sound by listening tests conducted by a representative jury. Finally, the problem is to achieve the desired character of the real sound.

This study focuses on the annoyance reaction to the external sound from a heavy truck diesel engine. The objective is to stress the relationships between engine modifications, PA descriptors and annoyance reaction.

2. METHODS AND PROCEDURES

The diesel engine, 9 litre, 6 cylinder in-line, is of a deep skirt type [5]. The problems of acoustic radiation are identified to the lower part (oil sump and crank case) and the frontal side (timing transmission cover) of the engine. To reduce sound level and to improve sound quality, different modifications were tested, see Figure 1 and Table 1 - 3.

Experimental Design

The engine modifications, were defined as variables in two distinct levels (Table 1). The experiment was subdivided in two groups. The first group contained engines in idling power (Table 2) and the second group comprised running conditions (Table 3).

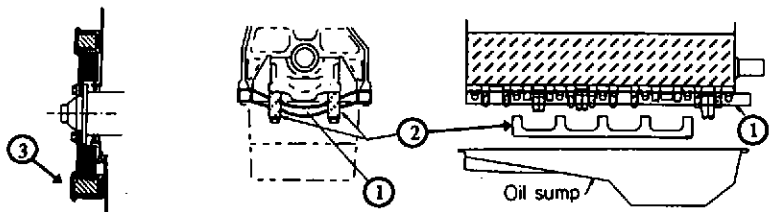

Fig. 1. Structure modifications of the lower and frontal part of the engine, (1) ladder frame, (2) bearing beam and (3) torsional damper cover [5].

Table 1. Variable definition for the experimental design

Variable	*Description*	*(low)* Level	*(high)*
X_{1ic}	Idling condition, speed(rpm); torque (Nm)	500; 20 (-)	620; 20 (+)
X_{1rc}	Running condition, speed(rpm); torque (Nm)	800; 800 (-)	1900; 370 (+)
X_2	Oil Sump softly coupled	no (o)riginal	yes (SO)
X_3	Ladder Frame	no (o)	yes (LF)
X_4	Bearing Beam	no (o)	yes (BB)
X_5	Covered Torsional Vibration Damper	no (o)	yes (CD)

Table 2. Design, idling power

Stimuli	X_{1ic}	X_2	X_3	X_4	X_5
1	-	SO	LF	BB	o
2	+	SO	LF	BB	o
3	-	o	LF	BB	o
4	-	o	LF	o	o
5	-	SO	LF	o	o
6	+	SO	LF	o	o
7	-	o	o	BB	o
8	+	o	o	BB	o
9	+	o	o	o	o
10	-	o	o	o	o
11	-	o	o	o	CD

Table 3. Design, run condition

Stimuli	X_{1rc}	X_2	X_3	X_4	X_5
1	+	SO	LF	BB	o
2	+	o	LF	BB	o
3	+	o	LF	o	o
4	-	o	LF	o	o
5	+	SO	LF	o	o
6	-	SO	LF	o	o
7	-	o	o	BB	o
8	+	o	o	BB	o
9	+	o	o	o	CD
10	-	o	o	o	o
11	+	o	o	o	o

Subjective Evaluation

The engine sounds were recorded in a hemi-anechoic room, by a MS-stereo-microphone (Neuman 69 fet) [6]. The microphone was positioned in front of the engine at 1m distance and 1m above ground.

The listening tests, carried out in an anechoic room, were conducted by trained and experienced subjects (10 males and 6 females) chosen from the staff of the university. All sounds were presented through a pair of loudspeakers. The listening position was kept constant for all subjects and the sound level was reduced by 17 dB compared to the original level.

The subjective response was recorded on a seven point scale ranging from "not at all annoying" to "very much annoying". To familiarise with the procedure, three stimuli were used as a test. Annoyance ratings were scaled by the sequential rating method [7,8].

Objective Evaluation

The sound pressure signal for each sound stimulus was measured by a single microphone (B&K 4133) in the listening position, with the subject not present. All PA descriptors (Table 4) were determined by post-processing of the acoustic signal, sampled to the disc in the FFT based measurement system (LMS CADA-X) or alternatively sampled in third-octave-bands by a B&K 2123 real-time analyser.

Multivariate Statistics

Principal component analysis (PCA) and partial least squares modelling (PLS) [10] were used to evaluate both subjective and objective data. PCA was used to determine the relationship and redundancy among the variables. PLS was used to develop prediction models that describe annoyance as a function of PA descriptors.

Table 4. PA descriptors

Descriptors	*Unit*	*Abbreviation*
Loudness	Sone[1]	N
Specific N	Sone/Bark [1]	N'
Sharpness	Bark, Acum[1]	SB, SA
ERR	dB [10]	ERR
Roughness	Smod [3]	RS
Fluct. Strength	Vacil [1]	FS
Impulsiveness	Kurtosis [9]	IK
Sound Level	dB	Lp, LA, LB, LC, LD
Periodicity	Hz [3]	PP

3. RESULTS AND DISCUSSION

Figure 2 shows some of the estimated PA descriptors (Table 4) for all sound stimuli. A variation between L_A and loudness can be observed. All modifications gave a reduction in loudness except the use of the BB in idling condition. A combination of LF and BB (ic3 & rc2) minimises loudness. The overall results indicate that an increased stiffness in the lower part of the engine reduces loudness and roughness.

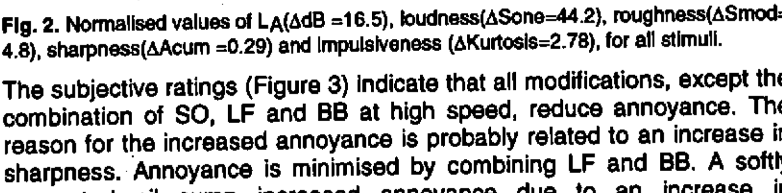

Fig. 2. Normalised values of L_A(ΔdB =16.5), loudness(ΔSone=44.2), roughness(ΔSmod= 4.8), sharpness(ΔAcum =0.29) and impulsiveness (ΔKurtosis=2.78), for all stimuli.

The subjective ratings (Figure 3) indicate that all modifications, except the combination of SO, LF and BB at high speed, reduce annoyance. The reason for the increased annoyance is probably related to an increase in sharpness. Annoyance is minimised by combining LF and BB. A softly connected oil sump increased annoyance due to an increase in sharpness and roughness.

The PCA, based on engine modifications, PA descriptors and scaled ratings (YSR), explained the data variation by 4 components for each group. Figure 4a shows the first two components due to idling condition. The first component, explains 50 % of data variation and indicates a relationship between, loudness, ERR and annoyance which are inversely proportional to the modifications LF and SO. For higher speeds (Figure 4b) a more complex behaviour is seen, since annoyance (YSR) is related to both components. The first component is described by loudness with an emphasis on frequencies in the ear resonance range (ERR). The structure modifications SO and LF are related to the second component which is proportional to periodicity (PP) and sharpness(SA), and inversily proportional to roughness(RS).

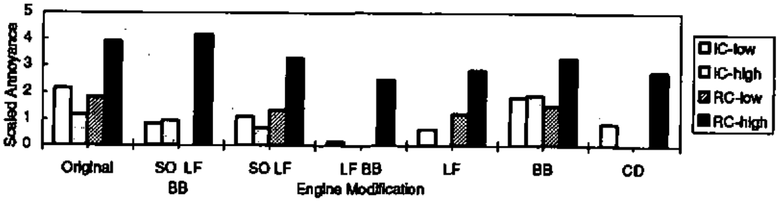

Fig. 3. Scaled values of annoyance as a function of engine modifications

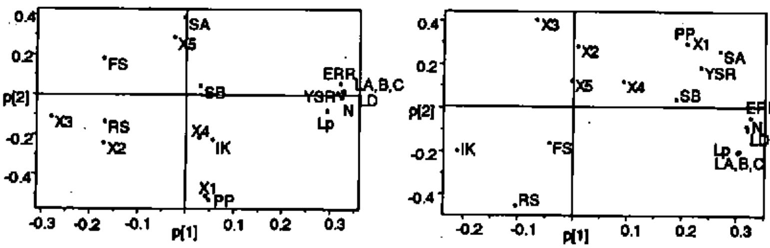

Fig. 4. Loadings for the two most significant principal components. a) idling c., b) run c.

The PLS model for idling condition describes 93% of annoyance variation as a function of loudness. The model for running condition is based on 2 significant components, describing 91 % of annoyance variation. The first component is related to loudness and periodicity and the second is related to sharpness and impulsiveness. The model indicates that lower levels of loudness, sharpness and impulsiveness minimise annoyance.

4. CONCLUSIONS

It is possible to find significant differences in perceived sound quality due to structure modifications of a diesel engine. In idling power however, the sound character remain unchanged. This is partly related to the recording position, which emphasises the acoustic radiation from the transmission cover, mainly described by the ERR frequencies.

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