Just noticeable differences of loudness and sharpness for earth moving machines

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Recent research on the improvement of the noise climate at the operator station of construction machines during real working conditions showed that loudness and sharpness are the parameters best correlated to the annoyance sensation. In order to verify the efficacy of some noise control solutions in improving the operator comfort conditions, it is necessary to detect the minimum differences in these metrics which are subjectively perceived: the just noticeable differences.
The subjective listening tests were performed following the classical Method of Limits on a jury of subjects tested one at a time. The subjects were asked to detect the just noticeable differences for both loudness and sharpness sensations, the step size of the stimulus being 0.3 sone and 0.02 acum, respectively. The test was repeated at three different signal presentation levels.
Results show that the just noticeable difference in loudness becomes greater as the overall sound pressure level of the signal increases. On the contrary, the just noticeable difference in sharpness has very small variations with the overall level. Focusing on the highest presentation level, 75% of subjects perceives a different sensation when sounds have a loudness difference of at least 0.8 sone and a sharpness difference of 0.04 acum.

1 Introduction

In recent years, earth moving machine manufacturers have had to cope with the request for machines with an ever-increasing performance level but compliant with more and more restrictive regulations in terms of environmental pollution (gaseous and particulate emission for internal combustion engines, and noise emission).

In particular, the aim of European policies concerning noise emission is that *no person should be exposed to noise levels which endanger health and quality of life*. For off-road machines, this approach involves the sound generated by the machine and transmitted either to the operator station, or elsewhere.

If we focus on the operator station of an earth moving machine, we deal with health and quality of the workplace. Therefore, the reduction of the exposure levels for the worker is a key element, but improvement of the noise quality in the working environment is also essential. Unfortunately, these aspects are not automatically correlated. In fact, the exposure to noise must almost always be assessed by means of physical parameters that have proved to be inaccurate indicators of human subjective response, especially for sounds exceeding 60 dB [1].

As in many other fields of application, besides the mandatory provisions, the construction machine industry is now oriented towards the sound quality approach [2]. Hence, at least in the last decade, research has been dealing with the identification of a set of acoustic and psychoacoustic metrics able to describe people's auditory perception of noise signals with respect to the annoyance sensation. Results from previous studies on these noise sources showed that Zwicker's loudness and sharpness are the parameters most related to the subjective perception of annoyance [3,4].

In order to verify the efficacy of some noise control solutions in improving operator comfort conditions, knowledge of the correlation between stimulus and sensation is not sufficient. In fact, tiny variations in stimulus magnitude may not lead to a variation in sensation magnitude. It is therefore necessary to detect the step size of the stimulus that leads to a difference in the hearing sensation, the *differential threshold* or *just noticeable difference, JND*. [5]

JNDs of amplitude and frequency, as well as duration changes of pure/complex tone or broad band noise, have been investigated for decades, but little is known regarding the JNDs of sound quality metrics in real noises [6]. This paper describes the results of specific listening tests carried out in order to evaluate the JNDs of loudness and sharpness of sounds recorded at the operator station of an earth moving machine.

2 Sound stimuli

The sound was binaurally recorded by means of a head and torso manikin located at the operator station of a compact skid-steer loader, in stationary conditions, with the engine idling at 2350 rpm.

The recorded signals were then post-processed following different steps:

1) to generate a sound stimulus with the same signal at both ears (diotic stimulus), in order to help listeners to concentrate only on the differences between the sounds having different loudness or sharpness, without being influenced by interaural differences;

2) to balance the spectral modifications that occur during playback, depending on the specific sound card and electrostatic headphone used for the listening tests;

3) to create sound stimuli with different loudness or sharpness values according to the design of experiments typical of the Method of Limits.

For the evaluation of loudness JNDs, the overall sound pressure level of the original sound was varied in order to change the total loudness value by interval steps of +0.3 sone and -0.3 sone. The sharpness value among these stimuli was kept constant.

Apart from the original sound, 9 sounds with higher loudness value and 9 with lower loudness value were created. The specific loudness of all these sound stimuli is reported in Fig.1 where the thick line represents the stimulus used as reference in the listening test.

For the evaluation of sharpness JNDs, the original sound was filtered in order to change the sharpness value by interval steps of +0.02 acum and -0.02 acum. This effect was achieved with a 1/3 octave band filter with a negative gain in the 40-80 Hz range and a positive gain in the 4-20 kHz range. The maximum difference in loudness among the stimuli with different sharpness values was less than 0.1 sone. As found in a similar study [6], although concerning a different sound source, such a difference should not influence the responses of subjects with respect to the sharpness feature.

Apart from the original sound, 9 sounds with higher sharpness value and 9 with lower sharpness value were created. The 1/3 octave band spectra for the sound pressure level are shown in Fig.2 in order to illustrate the filter effect.

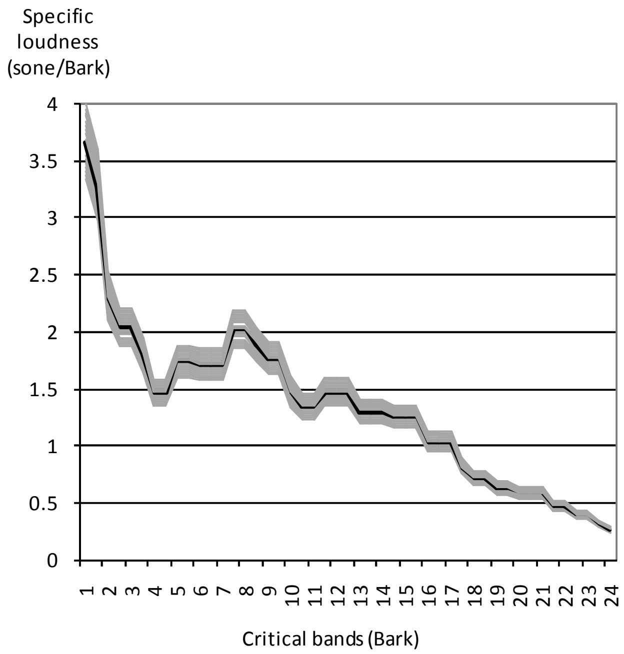

Fig.1 Specific loudness of the sound stimuli created for the loudness JNDs test

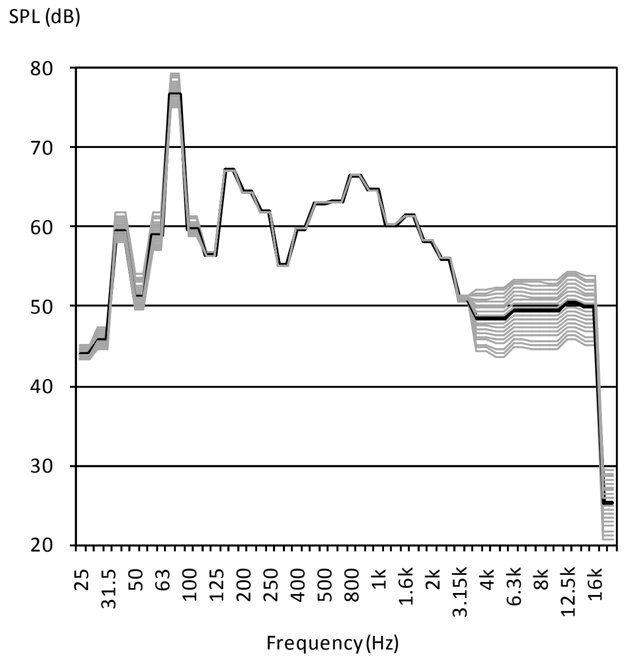

Fig.2 Sound pressure level of the sound stimuli created for the sharpness JNDs test

3 Subjective listening tests

There are different psychophysical methodologies used to determine differential thresholds. In this experiment the Method of Limits was chosen mainly for its simplicity.

In this method, two stimuli are presented in each trial and the subject is asked whether the second is greater than, less than, or equal to the first with respect to a certain parameter. The first stimulus is held constant (reference stimulus) and the second is varied by the experimenter in discrete steps [7].

The procedure is repeated several times in subsequent ascending and descending runs.

A more detailed description of the experimental procedure followed in each test session is reported here, referring to the first loudness test (see Table 1).

The reference stimulus (N = 32.1 sone) is presented first. Then, after a 1.5 s pause, a second stimulus is presented, with a loudness value (N = 30 sone) expected to be well below the difference threshold. Since the loudness difference (ΔN = 2.1 sone) is clearly detectable, the subject responds by saying that "the second stimulus is less loud than the first". The ascending run goes ahead with another pair of stimuli formed by the reference stimulus (always the same) and a second stimulus having a loudness value slightly higher than before (N = 30.3 sone). This process is repeated even when the subject no longer perceives the loudness difference (the two stimuli appear equal). The ascending run is terminated when the subject gives a reverse judgment, by saying that "the second stimulus is louder than the first", for two subsequent pairs.

At this point a descending run starts with a pair of stimuli formed by the reference stimulus (always the same with N = 32.1 sone) and a second stimulus having a loudness value known to be well above the difference threshold (N = 34.2 sone). The procedure is exactly the opposite of that used in the ascending run.

A total number of six runs (three ascending alternated to three descending runs) were planned for each loudness and sharpness test.

The whole experiment was divided into three test sessions, different from each other as far as the sound pressure levels of the reference stimulus are concerned (see Table 1 for details). In every test session each subject was asked to perform a test for first, detecting loudness JNDs, and then, sharpness JNDs. A few minutes rest was scheduled between the loudness and sharpness tests.

21 subjects (16 males and 5 females) took part in the first and second test sessions, while 16 subjects (12 males and 4 females) took part in the third test session.

The test was performed in a quiet laboratory room where the subjects were tested one at a time, and listened to the sound stimuli by means of high quality electrostatic headphones. 50 % of the listening jury had prior experience in subjective listening tests, but had never experienced this specific psychophysical procedure (Method of Limits). Moreover, 50 % of the listening jury were not familiar with the psychoacoustics parameters for which the evaluations were requested (loudness and sharpness).

At the beginning of each test, the experimenter gave the subject verbal instructions for the task he/she was asked to perform. The explanation concerned both the experimental procedure and the meaning of the noise features under investigation.

Then, a trial test was performed in order to verify whether the subject was able to detect differences in loudness and sharpness. For this aim, two pairs of sound stimuli were chosen on the basis of the loudness and sharpness JNDs found in a similar study [6]. In the loudness trial test, the sound stimuli had a loudness difference of 2.7 sone, and in the sharpness trial test, the sound stimuli had a sharpness difference of 0.18 acum.

Table 1 shows the structure of the whole experiment, also giving information about the metrics of the reference stimulus in each test.

	Loudness JNDs test	Sharpness JNDs test
1st test session (SPL of the reference stimulus around 80 dB)	Lp = 82.0 dB N=32.1 sone S=1.31 acum	Lp = 78.9 dB N=29.8 sone S=1.49 acum
2nd test session (SPL of the reference stimulus around 70 dB)	Lp = 73.1 dB N=18.0 sone S=1.30 acum	Lp = 69.0 dB N=15.6 sone S=1.47 acum
3rd test session (SPL of the reference stimulus around 60 dB)	Lp = 64.9 dB N=10.3 sone S=1.27 acum	Lp = 59.1 dB N=7.74 sone S=1.42 acum

Table 1 Reference sound stimuli for the six tests

4 Results

Some jury members complained about the difficult task. This happened especially for sharpness tests, even for subjects with prior experience both in listening tests and in psychoacoustics. It may be due mainly to the lack of experience in focusing attention on the perception of this sound feature.

The results of one subject were discarded because there was a clear evidence of misunderstanding of the test.

At the end of the listening tests, for each member of the listening jury it was possible to summarize the given judgments in a graphic form as shown in Fig.3.

Focusing on the loudness test, the Method of Limits resulted in a range of values in which the second stimulus is louder than the first (reference), a range in which the second is quieter, and a range in which the two sounds appear to have an equal loudness value. Similar results can be found for sharpness test, where “louder” and “quieter” becomes “higher ” and “lower” sharpness, respectively.

The differential threshold, or difference limen, for each subject may be estimated once the average upper and lower limens have been settled. The upper limen is halfway between louder/higher and equal judgments, and the lower limen is halfway between quieter/lower and equal judgments. The average limens are obtained by averaging the upper and lower limens across runs.

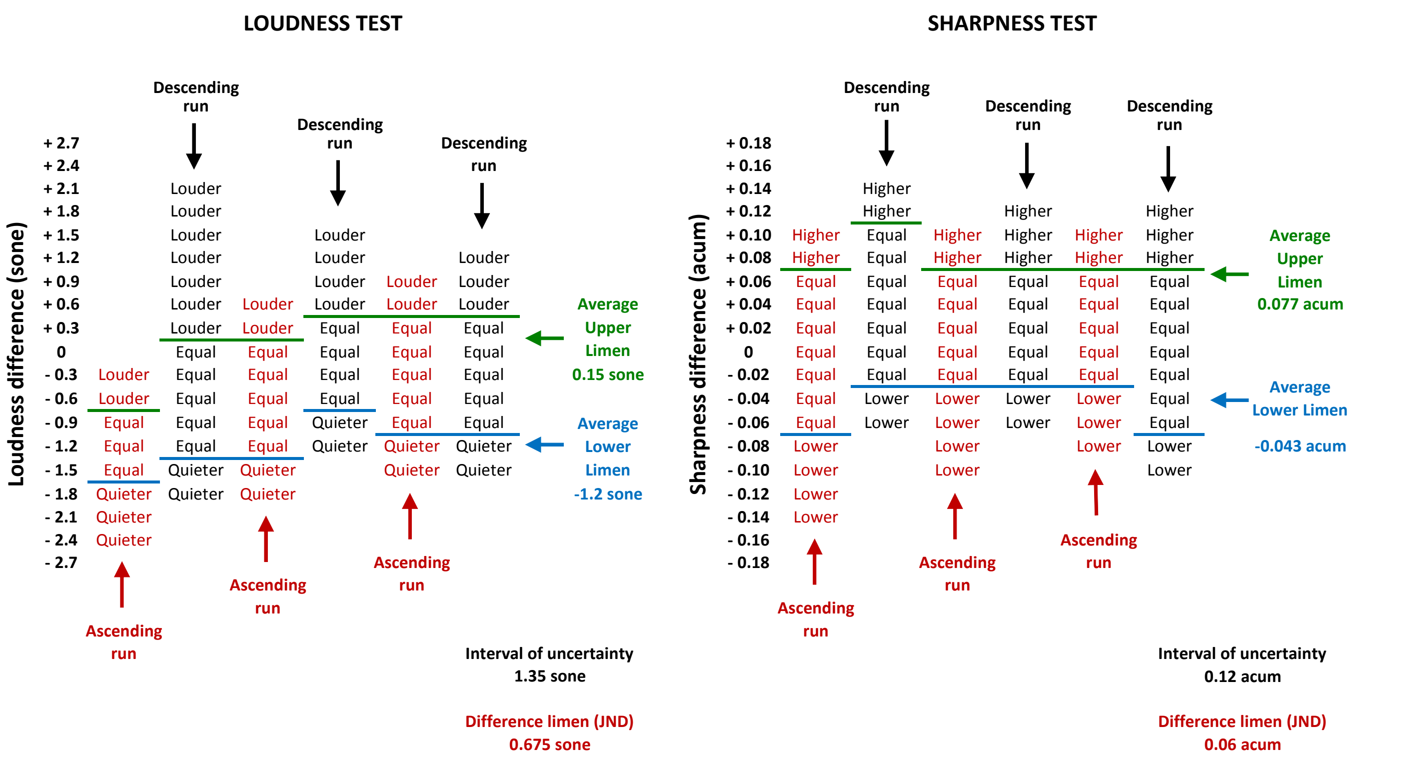

Fig.3 Judgments given by one subject for the differential thresholds of loudness and sharpness (SPL around 80 dB) using the Method of Limits

The range between the average upper limen and the average lower limen represents an interval of uncertainty, and the just noticeable difference, or difference limen, is generally estimated as one-half of this uncertainty interval. [7]

Once the difference limens were calculated for each subject, some statistical considerations could be outlined for the loudness and sharpness test, separately.

4.1 Loudness: just noticeable differences

Table 2 shows the results for the test of just noticeable differences in loudness. In this table, the variation range of the JNDs among the subjects and some percentile values are reported. The loudness value of the reference stimulus of each test is also specified.

The just noticeable difference becomes greater as the overall sound pressure level of the signal increases. This indicates that the greater the level, the more difficult it is for the subject to detect tiny loudness variations in the sounds.

This result recalls Weber's law saying that the size of the JND is a constant proportion of the original stimulus value. In this case, however, the proportion exists but is not constant.

	SPL around 80 dB	SPL around 70 dB	SPL around 60 dB
Loudness value	32.1 sone	18.0 sone	10.3 sone
Range	0.4 - 1.2 sone	0.3 - 1.2 sone	0.3 - 0.8 sone
50° percentile	0.7 sone	0.6 sone	0.4 sone
75° percentile	0.8 sone	0.8 sone	0.5 sone
90° percentile	1.0 sone	1.0 sone	0.7 sone

Table 2 Just noticeable differences for loudness tests

The just noticeable difference is defined as the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience.

For a single subject the calculation procedure is clear, but when the results of a group of people have to be described, a statistical descriptor has to be chosen. For this research, the 75° percentile could be considered appropriate. An average or median value, instead, would not guarantee that the improvement of the operator comfort conditions were extensively appreciated.

Cumulative distributions rather than unique values of just noticeable differences are more functional and make it possible to choose the just noticeable differences value depending on the specific target.

Fig.4 shows the loudness cumulative distribution for the three loudness tests having different sound pressure levels of the reference stimulus. The horizontal axis reports the loudness just noticeable difference, in sone. The vertical axis indicates the percentage of subjects detecting a variation in loudness sensation for a certain just noticeable difference in loudness. The scale of this axis is normalised to the number of subjects that took part in each test session.

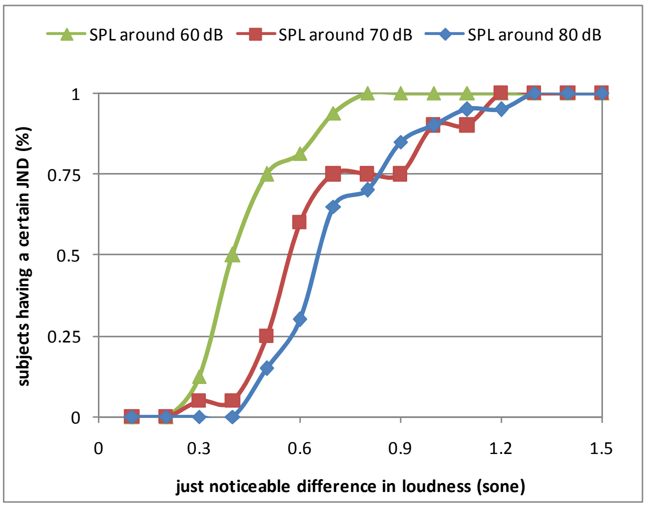

Fig.4 Loudness cumulative distribution

The variation of loudness detected by at least 75% of subjects is the abscissa corresponding to 0.75.

For earth moving machines where the sound pressure levels at the operator position are around 80 dB, the cumulative distribution for the highest presentation level must be considered. Therefore, the just noticeable difference in loudness is assessed as 0.8 sone.

4.2 Sharpness: just noticeable differences

Table 3 shows the results for the test of just noticeable differences in sharpness. In this table, the variation range of the JNDs among the subjects and some percentile values are reported. The sharpness value of the reference stimulus of each test is also specified even if, as expected, it is almost independent of the sound pressure level variation.

The just noticeable differences show little variations with the presentation level only for the 90° percentile and no specific results concerning Weber's law can be described. A specific test should be dedicated to this task.

	SPL around 80 dB	SPL around 70 dB	SPL around 60 dB
Sharpness value	1.49 acum	1.47 acum	1.42 acum
Range	0.02 - 0.07 acum	0.01 - 0.08 acum	0.02 - 0.06 acum
50° percentile	0.03 acum	0.03 acum	0.03 acum
75° percentile	0.04 acum	0.04 acum	0.04 acum
90° percentile	0.06 acum	0.04 acum	0.04 acum

Table 3 Just noticeable differences for sharpness tests

Fig.5 shows the sharpness cumulative distribution for the three sharpness tests having different sound pressure levels of the reference stimulus.

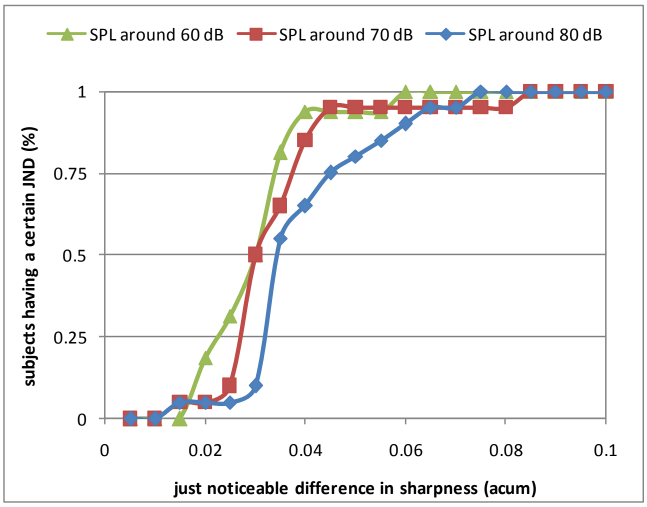

Fig.5 Sharpness cumulative distribution

Also for this psychoacoustic parameter, the just noticeable difference is defined as the minimum variation in sharpness detected at least by 75% of the jury subjects.

Consequently, for improving the noise climate at the operator station of earth moving machines, the just noticeable difference in sharpness is assessed as 0.04 acum.

5 Conclusions

Subjective listening tests following the Method of Limits were performed in order to detect the step size of a psychoacoustic parameter that leads to a difference in the hearing sensation.

Since previous studies on earth moving machinery showed that Zwicker's loudness and sharpness are the parameters most related to the subjective perception of annoyance, the just noticeable differences for these metrics were investigated.

Results show that the just noticeable difference in loudness becomes greater as the overall sound pressure level of the signal increases. On the contrary, the just noticeable difference in sharpness has very small variations with the overall level. Focusing on the highest presentation level, 75% of subjects perceives a different sensation when sounds have a loudness difference of at least 0.8 sone and a sharpness difference of 0.04 acum.

In order to verify the efficacy of some noise control solutions in improving the operator comfort conditions, the 75° percentile could be considered appropriate. In fact, a loudness variation that leads to a difference in loudness sensation perceived at least in 75% of cases justifies the technical and economical investments made by the manufacturers. An average or median value, instead, would not guarantee that the improvement of the operator comfort conditions were extensively appreciated.

Cumulative distributions rather than unique values of just noticeable differences are more functional and make it possible to choose the just noticeable differences value depending on the specific target.

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References

[1] R. Hellman, E. Zwicker, "Why can a decrease in dB(A) produce an increase in loudness?", *J. Acoust. Soc. Am.* 82(5), 1700-1705 (1987)

[2] M. S. Khan, C. Dickson, "Evaluation of sound quality of wheel loaders using a human subject for binaural recordings", *Noise Control Eng. J.* 50(4), 117-126 (2002)

[3] G. Brambilla, E. Carletti, F. Pedrielli, "Perspective of the sound quality approach applied to noise control in earth moving machines", *Int. Journal of Acoustics and Vibration* 6(2), 90-96 (2001)

[4] E. Carletti, C. Casazza F. Pedrielli, "Psychoacoustic characterisation of the noise at the operator position of a compact loader during real working conditions", Proceedings of 19th ICA, Madrid (2007)

[5] H. Fastl, E. Zwicker, *Psychoacoustics – Facts and models*, Springer-Verlag (2007)

[6] J. You, J. Y. Jeon, "Just noticeable differences of sound quality metrics of refrigerator noise", Proceedings of 19th ICA, Madrid (2007)

[7] S.A. Gelfand, *Hearing – An Introduction to Psychological and Physiological Acoustics*, 2nd ed., Marcel Dekker Inc., New York and Basel (1990)