From Noise Levels to Sound Quality: The Successful Approach to Improve the Acoustic Comfort

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1. Introduction

This work aims at presenting the experience of the authors in applying the "product sound quality" approach to the noise signals recorded at the operator station of some earth moving machines (EMMs) in order to improve the acoustic comfort for the operator.
For industrial products, the concept of "product sound quality" was defined by Blauert and Jekosch as "*…a descriptor of the adequacy of the sound attached to a product. It results from judgements upon the totality of auditory characteristics of the sound, the judgements being performed with reference to the set of those desired features of the product which are apparent to the users in their actual cognitive, actional and emotional situation*" (Blauert & Jekosch, 1997).
Referring to the operator station of an EMM, health and quality of the workplace are both important aspects to be taken into account. Therefore the reduction of the noise exposure levels and the improvement of the noise quality in terms of low annoyance are both key elements. Unfortunately, these aspects are not automatically correlated. According to the mandatory provisions, the exposure to noise must be assessed by means of physical parameters that have proved to be inaccurate indicators of subjective human response, especially for sounds exceeding 60 dB (Hellman & Zwicker, 1987).
This chapter collects the main results of the research carried out by the authors in the last five years in order to overcome this problem and to identify a methodology that is able to establish the basic criteria for noise control solutions which guarantee the improvement of the operator comfort conditions (Brambilla et al., 2001).
All the results presented below refer to investigations carried out on compact loaders. The particular interest in this kind of machine is due to the fact that it is widely used not only for outdoor work but also in the activities of building construction and renovation. In addition, the compact loader is one of the worst machines as far as the noise emission is concerned. Due to its compactness, indeed, the operator station is located just over the engine compartment which cannot be completely insulated from the outside due to overheating problems. As a consequence, noise and vibration levels at the operator station are extremely high, causing very uncomfortable conditions for workers.
Although the enforcement of the results described in this work is limited to the assessment of annoyance for this kind of product, the philosophy of this approach has a general validity which is to be customised for each different application.

This chapter is divided into three main sections:

- the first section describes the methodologies applied to carry out the binaural recordings at the operator station of these machines;
- the second section presents the psychometric technique chosen for the experiments and the procedures applied to the subjective evaluations of the noise signals;
- the third section collects the most significant experimental investigations and their relevant results.

2. Binaural recordings

Binaural technology offers the best technical solution to pick up and store sound in a way which is compatible to human hearing and then is a fundamental component of an experimental approach oriented to the sound quality evaluation.

2.1 Binaural recording technique

Binaural techniques for aurally-adequate sound recording and playback have evolved greatly in recent decades with the development of digital systems for signal recording and very fast processors for signal processing.
The basic principle of binaural techniques takes into account that the sensation of any sound is processed by the human auditory system from the two sound pressure signals arriving at the right and left ears. It enables us not only to identify noise sources but also to localise them in a 3D space. Starting from these features and performance of the human auditory system, binaural techniques require that sounds are picked up by two microphones and that recordings are performed in such a way that the "*signals can faithfully reproduce all aspects of the auditory experience also with regard to the spatial characteristics of sounds and their direction of origin*" (Møller, 1992).
The playback of the recorded signals is also an important step in the binaural chain as listening and subjective judgements are essential in assessing the quality of sounds. For this reason, the original sound has to be accurately reproduced, counterbalancing the unwanted spectral modifications that occur during recording and playback.
Currently, two methods can be used for binaural recordings:

- the use of artificial heads (faithfully reproducing head, torso and ears of a listener);
- the use of special miniature microphones, positioned at the ear canal of real subjects.

Both methods were used in the experimental investigations.

2.1.1 Artificial heads

All the artificial heads available on the market reproduce an average human head in such a way that sound waves reaching the head follow the same path that they would follow to reach the ears of a real listener placed in the same location. They differ in many details including the shape and the dimensions of nose, orbit, pinna, ear canal and the positions of microphones. These latter can be located at varying positions along the ear canal, from its entrance to the eardrum.
All of these systems are highly reliable with regard to the aurally-adequate sound recording as well as the playback. To faithfully reproduce all aspects of human auditory perception, these systems include specific transfer functions which take into account the different effects on the sound due to the body, the head and the outer ear.

Referring to the investigations at the operator station of compact loaders, as the space was insufficient to place an artificial head beside the worker, the head-torso manikin was placed at the operator station. The use of this system was obviously limited to the case of noise measurements taken in stationary conditions.

2.1.2 Real head recording system

The use of very lightweight devices consisting of miniature microphones or probes positioned at the entrance of the ear canal of a real subject is certainly a feasible alternative to that of artificial heads (Møller, 1992). The advantage of this approach is that it does not require any correction referring to the ear canal and the resulting recordings contain complete spatial information. The chain of reproduction of the signals, however, must be carefully developed and specific equalization curves are to be introduced to remove all the changes induced by the various components of the chain.
Referring to the investigations at the operator station of compact loaders, this technique was extensively used for all the noise measurements carried out in dynamic conditions.

2.2 Noise measurements referring to loaders

A sample of 41 compact loaders belonging to six different families (A, B, C, D, E, F) regarding manufacturer, dimension and engine mechanical power, was involved in the experiments. All the binaural recordings were made at the operator station of these machines, both in stationary and real working conditions, in order to be able to reproduce different operations of loaders. Measurements were taken in open areas, generally used for EMM testing, where stockpiles of different materials could be found.
Referring to stationary conditions, binaural recordings were performed using the Cortex System MK1 which consists of a dummy manikin, a torso simulator and a digital DAT recorder HHB PDR 100. This system was placed at the operator station and measurements were carried out while the tested machine was in stationary idle condition, with the engine running at a fixed speed. These measurements involved five different loaders of the same family (*F1* to *F5*).
Referring to the dynamic conditions, binaural recordings were obtained by means of two miniature pre-polarised condenser microphones placed at the entrance of the operator's ear canals (binaural microphones B&K 4101) while the tested machine was performing the typical work cycle for a loader, which includes two main operations: the loading of material from a stockpile and the unloading of it in a defined position. These measurements involved all the remaining machines. Besides the noise signals, also the tachometer signal was recorded in order to relate at each time the frequencies of the noise spectrum to the rotational frequencies of the different components of the machine.
Twenty-one loaders of five different families (*A1* to *A5*, *B1* to *B5*, *C1* to *C5*, *D1* to *D3*, *E1* to *E3*) repeated this work cycle with two kinds of materials: gravel and loam. Fifteen other machines of three different families (*A6* to *A10*, *B6* to *B10*, *C6* to *C10*) performed the same work cycle without any material (simulated cycle).
In total, 62 different binaural noise signals were available for the different investigations. Figure 1 shows the noise measurement setup both for stationary (left) and dynamic (right) conditions.

Fig. 1. Binaural recordings

3. Subjective listening tests

Listening test results show a higher variance than that usually encountered in results obtained using instrumental measurements (Blauert, 1994). However, this high uncertainty can be greatly limited by choosing the most appropriate psychometric technique depending on the signals to be characterised and on the listening jury (Fiebig & Genuit, 2010).

3.1 Psychometric techniques

The several psychometric techniques can be broadly divided into two groups: the *absolute* procedures and the *relative* procedures (Van der Auweraer & Wyckaert, 1993).
In listening tests following the *absolute* procedures, the subject has to listen to a sound and judge it referring to one or more of its attributes. In listening tests following the *relative* procedures, on the contrary, the assessment by the subject results from the comparison between at least two different sounds.
In general, the *absolute* classification of a set of sound stimuli or their arrangement in an ordered list according to some criterion, is a process which sometimes can be inappropriate as it involves a series of psychological factors which are uncontrollable. In addition, when the sound stimuli chosen for listening tests are very similar with respect to certain attributes, tests according to absolute procedures can be very difficult, especially if they involve non-expert subjects. In these cases it is advisable to use a relative procedure (Bodden et al., 1998).
A further classification of psychometric procedures is based on the distinction between *non adaptive* and *adaptive* procedures (Gelfand, 1990).
The *non adaptive* procedures include “classic” methods such as:

- the *sequential* procedures (method of limits, method of adjustment), for which the listening level of the sound stimulus is varied step by step or continuously, but always with an ascending or descending sequence (from the lowest to the highest level or vice versa);
- the *non sequential* procedures (method of constant stimuli), for which the listening level of the sound stimulus changes according to a predefined random sequence.

The *adaptive* procedures include methods such as the Békésy's Tracking Method, the Up-Down (Staircase) Method and the PEST procedures (Gelfand, 1990). In these procedures it is necessary to adjust the listening level of a sound stimulus on the basis of the answer given by the subject referring to the sound stimulus previously heard.

3.2 Rating scales

In listening tests the choice of the rating scale on which the subjects express their opinion is a key element to avoid ambiguity in the responses. According to a classification proposed by Stevens in 1951, the rating scales can be divided into: *nominal* scale, *ordinal* scale and *interval* scale (Stevens, 1951).
In *nominal* scales, variables take values represented by names or categories. These values cannot be put in order or treated algebraically. The only relationship that can be established between the various results is that of equality or diversity.
In *ordinal* scales, variables take values which can be sorted by some criterion. Relationships of "greater", "equal", "less" can be established between the different results but without any possibility to establish the distance between classes.
In *interval* scales, each variable is represented by a quantitative value. Therefore, either the different positions on the scale or the distances between the values are significant. In particular, the amplitudes of the intervals between equidistant positions on the scale represent equal differences in the measured phenomenon.
Depending on the type of scale chosen for tests, the most appropriate methods for statistical analysis have to be identified. For *nominal* and *ordinal* scales non-parametric statistical methods are preferred (Spearman correlation coefficient, Kendall's correlation coefficient), while for the *interval* scale the parametric statistical methods are more suitable.

3.3 Procedures applied to the subjective investigations referring to loaders

The binaural noise signals recorded at the operator station of the compact loaders under test were all very similar with respect to the perception of annoyance. A direct estimation of them with respect to this attribute following an *absolute* psychometric procedure would have been very hard, especially for non expert subjects. On the contrary, a *relative* comparison between sounds made the task much easier for the subject and made the detection of the difference among the sound stimuli easier to be assessed. So, the listening tests performed in the several investigations were all carried out according to the relative procedure of paired comparison (Kendall & Babington Smith, 1940).

3.3.1 The listening sequence of sound stimuli

According to the paired comparison procedure, each sound stimulus is directly compared to the others and the subject is asked to give his opinion after listening to each pair. In the several experiments, the *classic* and the *modified* versions of this procedure were both applied: in the *classic* version, the subject had to choose the sound he preferred in each pair and no ties were permitted; in the *modified* version, on the contrary, the subject was permitted to judge the sounds in the pair equally (David, 1988).
In any case, the main advantage of this procedure was that the subject was asked to judge only two stimuli at a time and this helped his concentration and reduced the probability for him of inconsistent judgments.

The number of possible pairs from a group of n sound stimuli is given by the number of combinations of two elements taken in this group, namely by :

$$\binom{n}{2} = \frac{n!}{(n-2)!\,2!} = \frac{n(n-1)}{2} \qquad (1)$$

In the listening tests, the two sounds of each pair had always the same duration so that the judgement given by the subjects was not influenced by a different listening period. In addition, the two sound stimuli were always separated by a pause so that the subject could distinguish each of them and was not confused by their similarity. The duration of this pause, however, was not so long as to impair the memory of the first sound heard by the subject.
In order to avoid any sequence effect, all the pairs were arranged in a random sequence according to the well established *digram-balanced Latin Square* design (Wagenaar, 1969). In such a way the first pair to be judged and the order of the pairs in the sequence were different for each subject.

3.3.2 The listening session

All the listening tests were performed in the laboratory, under stable, controlled boundary conditions, with the great advantage of high reproducibility of the test results.
The sound stimuli were presented to the subjects through a high-quality electrostatic headphones (STAX Signature SR-404), with a flat response in the 40-40000 Hz frequency range, after being modified to take into account the transfer function of the headphones and the specific sound card. Listening through headphones reduces the ability of a correct spatial sound localization but for sounds recorded in earth moving machines this effect is not so important as the frequency content is concentrated in the medium-low frequency range that is not directional.
Each listening session started with a *learning* phase during which the person responsible for the experiment gave the subject verbal instructions needed to understand the procedure for the test. This phase was a critical point of the listening session. An interaction between subject and the experimenter was necessary in order to clarify possible doubts before performing the test. This interaction, however, should not be excessive in order not to influence or interfere with the judgements given by the subject.
At the end of this phase, the test started. The subject, after listening to each pair of sound stimuli, was allowed to listen to the pair again as much as necessary. When ready, he gave his rating according to the rules of each specific investigation.
Each listening session ended when the subject had judged all the pairs of sound stimuli in the sequence.
The same procedure was then repeated for all the subjects of the jury involved in that specific test.

3.3.3 The jury of subjects

In listening tests each subject of the jury acts as a measurement device to measure his own perception; so, he must have normal hearing. A further important aspect to take into consideration in the choice of a listening jury is the experience of the subjects involved in the tests. This is related to their familiarity with listening tests and/or with the sounds under examination (Brambilla et al., 1992).

In the several investigations aimed at improving the acoustic comfort at the operator station of compact loaders, the operators were only seldom involved in the listening tests because of the difficulties in finding normal hearing persons. The jury generally included students and/or researchers who were not familiar with these kinds of noise signals but had some knowledge of acoustics and sometimes also prior experience in listening tests.
Nevertheless, the choice of subjects not familiar with EMM sounds did not limit the reliability of the results. An investigation carried out by the authors to verify whether the experience on the use of these machines could provide additional value in the subjective ratings compared to those by non expert subjects, showed similar results between these two groups (Carletti et al., 2002).
The number of subjects involved in the tests varied form test to test but it was always adequate to ensure the statistical significance of the results.

3.3.4 Preference matrices

The ratings given by each subject for all the pairs of sound stimuli in the listening sequence were arranged in a matrix, called the *preference matrix.*
In this matrix, the general element x_{ij} (i = row index and j = column index) represented the judgement expressed by the subject referring to the comparison between stimulus i and stimulus j.
When the specific test was carried out according to the *classic* version, each of these elements could take only the value 0 or the value 1, depending on the preference given by the subject (stimulus j preferred to stimulus i or vice versa).
When the specific test was carried out according to the paired comparison *modified* version, each matrix element could also take the value 0.5 when the two sound stimuli in the pair were equally rated by the subject.
Table 1 shows an example of the preference matrix in the case of a classic paired comparison test involving six sound stimuli (A-F).

	A	**B**	**C**	**D**	**E**	**F**
A		0	0	0	0	0
B	1		0	1	0	0
C	1	1		1	1	1
D	1	0	0		0	0
E	1	1	0	1		1
F	1	1	0	1	0	

Table 1. Preference matrix of a subject for a test involving six sound stimuli (A, B, C, D, E, F)

In this matrix the sum by rows gives the preference of each sound stimulus when compared to all the others.
Whichever method was applied, the subjective responses of the entire listening jury were arranged in the *overall preference matrix* which was obtained by adding the scores of the preference matrices of each subject, after the exclusion of the subjects who did not pass the necessary consistency checks explained in the following.

3.3.5 Consistency check of each subject

According to the procedure defined by Kendall and Babington Smith (Kendall & Babington Smith, 1940), in every listening test the *consistency* for each subject and the *agreement* among the subjects have to be evaluated in order to "*guarantee the control of the variance due to the emotional state of the judging individuals*" (Blauert & Jekosch, 1997).
To test for the *consistency* of each subject, two different checks were carried out in the several experiments: a) the check regarding the number of circular triads in the data set; b) the check regarding the judgement given by the subject to the repeated pair of stimuli.

a) Circular triads

In a paired comparison test involving three signals (A, B, C), the judgements given by a subject on comparisons "AB", "BC" and "AC" can be graphically represented using a triangle, usually called *the triad*. Under the hypothesis that a subject chooses A in the first comparison between (A→B) and B in the second comparison (B→C), the choice of C in the third comparison (C→A) does not obey the transitive property and therefore identifies an inconsistency which is graphically represented by a *circular triad*, as shown in figure 2(b).

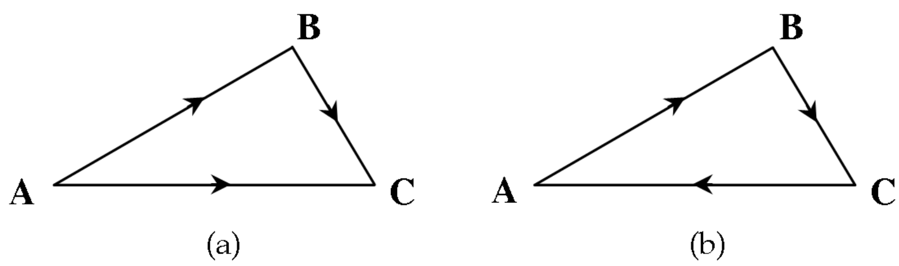

Fig. 2. Not circular triad (a): consistency - Circular triad (b): inconsistency

Referring to the investigations relating to loaders, the paired comparison test often involved 6 sound stimuli. The preference matrix for a classic test may be represented either in tabular form (as previously shown in table 1), or may be represented geometrically as in figure 3. This latter method may help in determining the number of circular triads contained in this polygonal representation.

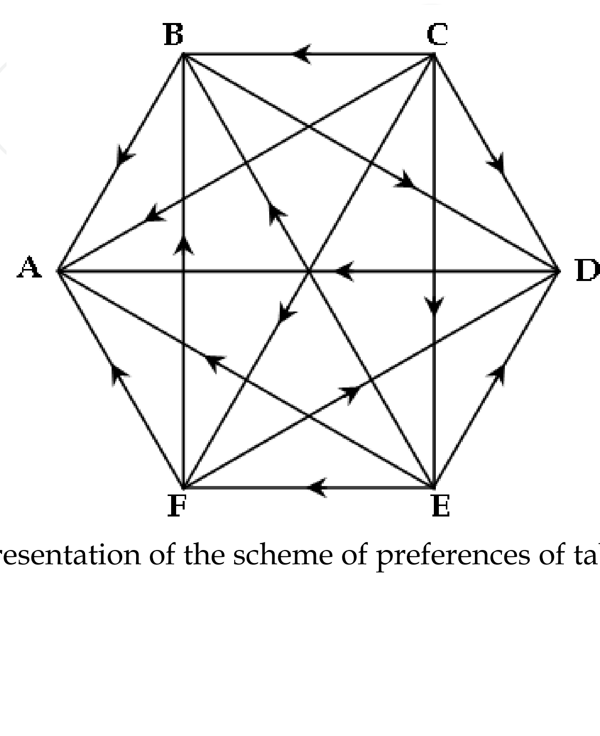

Fig. 3. Geometrical representation of the scheme of preferences of table 1.

In a general test involving *n* sound stimuli, for each subject the consistency coefficient was calculated on the basis of the number (d) of *circular triads* found in the complete set of judgements, referred to the maximum number of possible *circular triads* for that set of n sounds (d_{max}) (Kendall & Babington Smith, 1940):

$$K = 1 - \frac{d}{d_{\max}} \tag{2}$$

The value of this coefficient was then compared to its expected value E(K), calculated under the hypothesis that the observed circular triads were normally distributed (see tables in the Kendall and Babington Smith manuscript). Values of K smaller than E(K) corresponded to a data set where a tendency for inconsistent judgements was observed.

b) Repeated pair

One of the easiest ways to check whether people are consistent with their own answers is to ask them to judge the same pair of sound stimuli twice and compare the results. This check was considered successful when the subject gave concordant answers. However, taking into account the high variability in the subjective perception and the possibility that such an inconsistency could be random or unique, the failure of this test was not considered a sufficient condition to consider the subject unreliable and this check was always complemented by the previous test based on the circular triads.

3.3.6 Agreement among several subjects

To test for the *agreement* among the subjects, the *coefficient of agreement* was calculated, which takes into account the number of concordant judgements between pairs of subjects (Kendall & Babington Smith, 1940). In a test involving n sound stimuli and m subjects, if x_{ij} is the element (i,j) of the preference matrix, the agreement coefficient is defined as:

$$u = \frac{2 \cdot S}{\binom{m}{2} \cdot \binom{n}{2}} - 1 \tag{3}$$

where S is the total number of agreements between pairs of subjects, derived from the following equation:

$$S = \sum_{i,j} \binom{x_{ij}}{2} = \frac{1}{2} \cdot \sum_{i,j} x_{ij}(x_{ij} - 1) \tag{4}$$

The statistical significance of u strictly depends on the probability that its value is exclusively a random value.
In the several experiments, the probability to obtain a specific value of u, as a function both of the distribution of each subject judgments and of the distribution of the judgments given by all the subjects regarding each specific matrix element was obtained by considering the variable (Kendall & Babington Smith, 1940):

$$Z = \frac{4 \cdot S}{m-2} - \frac{m(m-1)(m-3)n(n-1)}{2(m-2)^2} \tag{5}$$

This variable follows the χ^2 distribution, with a number of degrees of freedom given by:

$$\frac{m(m-1)n(n-1)}{2(m-2)^2} \tag{6}$$

When the *modified* paired comparison method was applied, a slight different procedure was used to calculate the *agreement* coefficient u. According to this procedure, each matrix element with value 0.5 has to be excluded from the calculation of the overall judgements and the modified *agreement* coefficient u_m *is defined by:*

$$u_m = \frac{2 \cdot S}{S_{\max}} - 1 \quad \text{and} \quad S_{max} = \sum_{i=1}^{X} \binom{k_i}{2} + \binom{m}{2} \cdot \left[\binom{n}{2} - X \right] \tag{7}$$

where X is the number of the preference matrix elements with value 0.5 and S_{max} is given by:

$$S_{max} = \sum_{i=1}^{X} \binom{k_i}{2} + \binom{m}{2} \cdot \left[\binom{n}{2} - X \right] \tag{8}$$

4. The milestones in the investigations referring to loaders

This part of the chapter collects the most significant experimental investigations carried out on compact loaders. The particular interest in this kind of machine is due to the fact that it is widely used. Thanks to its compact size, it goes where bigger machines can not, has a reduced cost, it is easily transportable, agile and productive. Unfortunately, this compactness makes it one of the worst machines as far as the noise emission is concerned, as the operator is very close to the main sources of noise (engine and hydraulics). Consequently, noise and vibration levels at the operator station are extremely high, causing very uncomfortable conditions for workers.

4.1 Noise signals and auditory perception of annoyance

This investigation was performed in order to better understand the relationship between the multidimensional characteristics of the noise signals recorded at the operator position in different working conditions and the relevant auditory perception of annoyance (Carletti et al., 2007).

The tests involved six binaural signals recorded at the operator station of three loaders belonging to the families A, B, and C, while these machines were repeating the same work cycle which included two main operations: the loading of the material from a stockpile and the unloading of it in a specific position. In the following these machines will be indicated as *A1*, *B1*, and *C1* and the different kinds of material as L (loam) and G (gravel).

4.1.1 Objective parameters

Based on the results of a study concerning the sound quality evaluation of wheel loaders (Khan & Dickson, 2002), several acoustic and psychoacoustic parameters were calculated for the left and the right signals, separately. This set included: the overall sound pressure levels L_{eq} and L_{Aeq} (in dB and dBA), the mean values of loudness (in sone), sharpness (in acum),

fluctuation strength (in vacil) and roughness (in asper). Referring to the psychoacoustic parameters, they were all calculated according to the models proposed by Fastl and Zwicker (Fastl & Zwicker, 2006).
The results obtained for the six noise signals are summarised in table 2 (columns 3 to 8), while the frequency content of these signals is well described by the sonograms of the sound pressure level shown in figure 4, which refer to the different machines and working conditions.

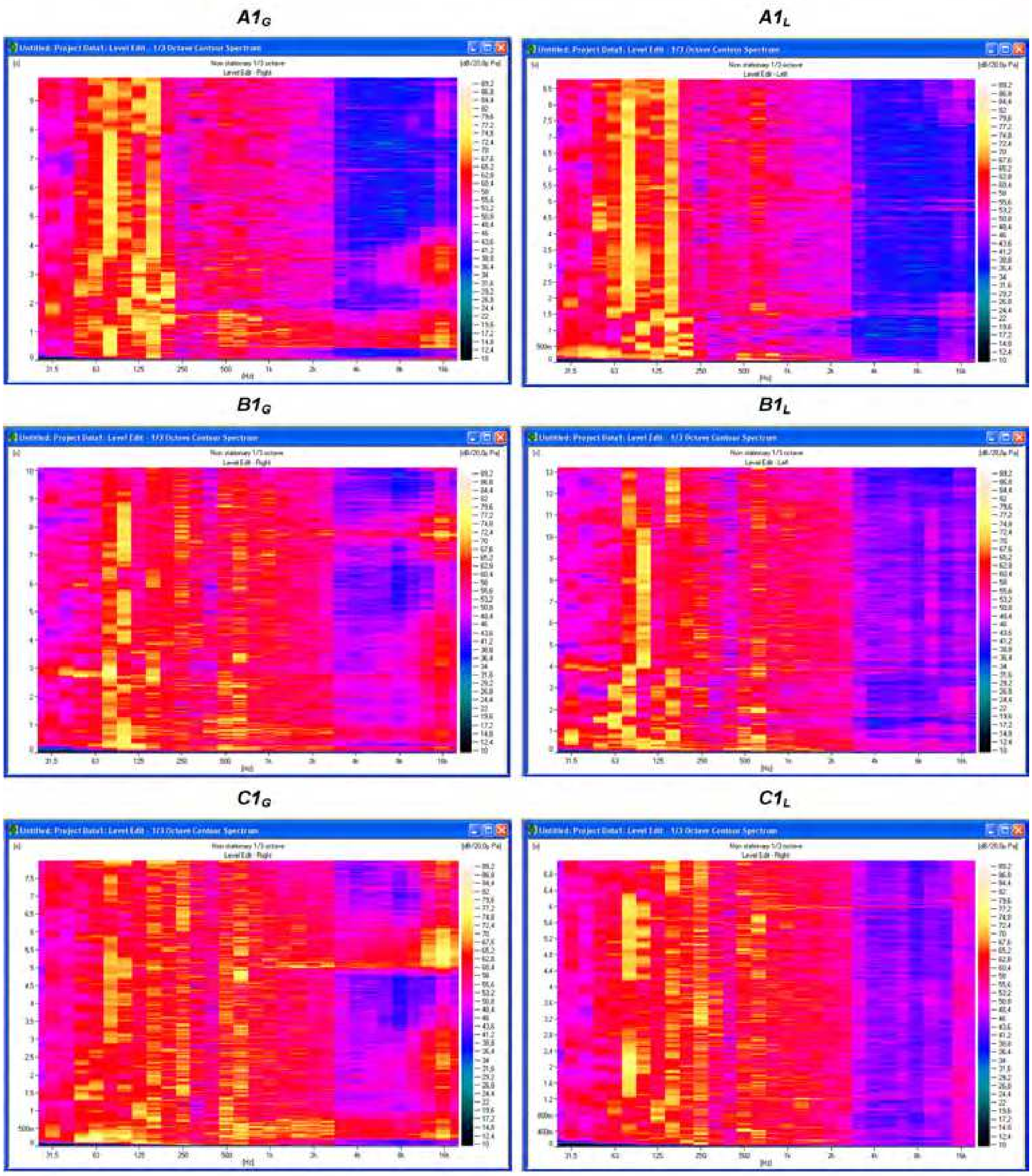

Fig. 4. Sonograms of the sound pressure levels: gravel (left) and loam (right)

Taking into account that during work the engine rotational speed of these machines ranged from 2000 to 2500 rpm, three interesting frequency intervals can be recognised.
The first one, in the 40-400 Hz frequency range, is directly related to the engine noise (engine rotational frequency, firing frequency and higher orders).
The second one, in the 500-3150 Hz frequency range, is related to the noise generated by the engine cooling system and the hydraulic system, this latter which drives arm, boom and bucket. In particular, at frequencies above 1kHz the noise contribution of the hydraulic system becomes the dominant one.
Finally, the third interval, at frequencies above 4 kHz, is related to the noise generated by the interaction between equipment and material or between various metallic parts of the machine (occurring, for example, when the actuators reach their travel limit).
The difference between these sonograms is significant. At the engine characteristic frequencies the noise levels are higher for *A1* than for *B1* and *C1* while at the hydraulic system characteristic frequencies the opposite occurs. At frequencies above 4 kHz, the noise components are always higher during operations with gravel than with loam, regardless of the machine used.

4.1.2 Subjective evaluations

All the possible pairs of the six binaural signals recorded during the work cycle with gravel and loam were presented to a group of 19 normal-hearing subjects (17 males and 2 females), all non expert subjects, that means without experience in listening tests or in the evaluation of the earth moving machine noise. All tests were performed according to the procedures described in paragraph 3.3. After listening to each pair of sound stimuli as many times as necessary, the subject had to answer to the following question: "Which of the two sounds is more annoying? *Sound 1* or *Sound 2*". No ties were permitted.
All the ratings given by the subjects satisfied the consistency tests and were included in the analysis process. The subjective ratings were arranged in matrices and then the annoyance overall score for each stimulus was obtained in terms of the number of cases it was judged more annoying than all the other ones. This value, normalised to the maximum score that the stimulus itself could have obtained, is reported in the second column of table 2.

Machi-nes	**Annoyance Subj. ratings (%)**	**L_{eq} (dB)**		**L_{Aeq} (dBA)**		**Loudness (sones)**		**Sharpness (acum)**		**Roughness (asper)**		**Fluctuation strenght (vacil)**	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
$C1_G$	0.99	78.7	78.6	74.1	73.8	32.5	31.5	1.77	1.64	1.29	1.31	1.13	1.22
$B1_G$	0.78	77.6	77.0	72.6	71.7	29.8	28.2	1.68	1.58	1.37	1.35	1.13	1.08
$A1_G$	0.43	78.5	78.3	69.5	69.4	25.3	24.7	1.44	1.37	1.72	1.77	1.06	1.03
$C1_L$	0.39	77.6	77.3	72.3	71.7	29.7	28.5	1.49	1.39	1.44	1.39	0.67	0.66
$B1_L$	0.22	76.7	75.9	71.4	69.8	26.7	24.4	1.43	1.37	1.44	1.42	0.81	0.79
$A1_L$	0.19	78.4	78.0	67.5	67.2	22.3	22.0	1.22	1.19	1.57	1.71	0.96	0.85

Table 2. Subjective annoyance ratings and acoustic/psychoacoustic parameters

4.1.3 Results

As shown in table 2, the *C1* machine handling gravel ($C1_G$) was the most annoying (99%), whilst the *A1* machine handling loam ($A1_L$) was rated the least annoying (19%).
Referring to the noise emissions of the machines handling different materials, the overall levels indicated in table 2 and the sonograms in figure 4 show that when the machine is working with loam, the overall noise emission is generally lower than that generated when working with gravel, regardless of the machine characteristics. The loam seems to have a damping effect on the different noise components both when the machine is loading the bucket and when it is transporting the material.
Referring to the different machines, *C1* was always judged more annoying than *B1*, and *B1* was always judged more annoying than *A1*, for each handled material. The annoyance ratings greater for *C1* than for *B1* could be simply related to the highest noise levels. On the contrary, the annoyance ratings greater for *C1* and *B1* than for *A1* could not be explained in terms of the overall noise levels but in terms of the highest noise levels emitted by *B1* and *C1* at the characteristic frequencies of the hydraulic system and at frequencies higher than 4 kHz.
The spectral characteristics described above clearly point out the relevance of the noise components at medium and high frequencies in affecting the subjective evaluation of the sound with respect to its annoyance. The subjective ratings of annoyance, however, cannot always be explained taking into account only the energetic characteristics of these signals. As an example, $A1_L$ (19% annoyance rating) has an overall level higher than that of $B1_G$ (78% annoyance rating), even if the first signal is judged significantly less annoying.
This example highlights the absolute necessity to complement this energetic analysis with other considerations involving also the psychoacoustic parameters and their variability over time.
The Pearson correlation coefficients with the annoyance ratings were calculated for all the parameters in table 2. The best correlation was obtained with sharpness (r = 0.94) and relatively high values were also found with loudness (r = 0.87) and L_{Aeq} (r = 0.85). The parameter least correlated with the annoyance ratings was L_{eq}, with r = 0.40.
In addition, for each objective parameter the correlation coefficient between left and right signals was also evaluated. These correlations were consistently very high (almost equal to 1) for all the parameters. For this reason, only the signal with the highest correlation coefficient with respect to the subjective judgements was chosen for analysis.
Referring back to $A1_L$ and $B1_G$ noise signals, the different subjective judgements can be found in the sharpness value or, better, in its time history. Figure 5 shows some percentile values of sharpness for the different machines and materials.
The sharpness percentiles of $A1_L$ are significantly lower than those of $B1_G$. In addition, under working condition with gravel, all the noise signals have very high values of percentile sharpness S_5 with respect to their average sharpness S_{50}. As S_5 percentile describes the variability over time of these signals much better than S_{50}, the very high values of this parameter underline that prominent noise events occur very frequently under working conditions with gravel and this leads to a negative subjective evaluation.
The good correlation of S_5 with the annoyance ratings (r = 0.91) and the possibility to take into account variability over time of the noise signals makes this parameter very important for acoustic comfort improvement. Moreover, considering that the auditory sensation of this parameter greatly depends on the signal content at medium-high frequencies (Fastl &

Zwicker, 2006), the above results gave a further proof of the relevance on the subjective ratings of annoyance of the noise components generated both by the hydraulic system and the handling of materials.

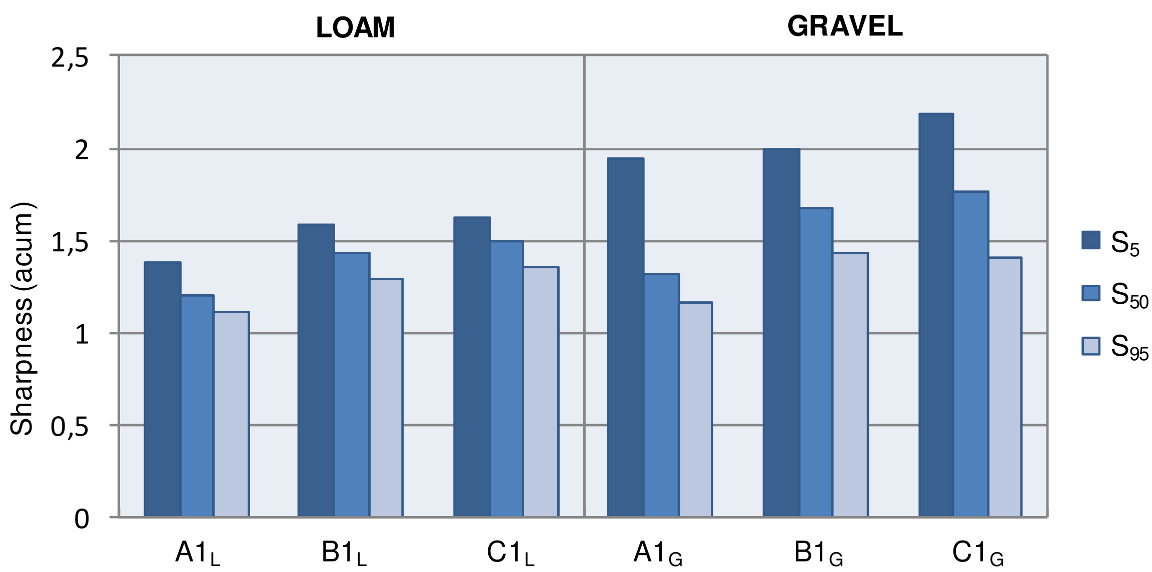

Fig. 5. Sharpness percentile graphs for the different machines and materials handled

A deeper insight of the differences in the subjective judgements for machines handling different materials can be obtained by analysing the time-dependent characteristics of the noise signals in terms of loudness distributions. As an example, figure 6 shows the loudness cumulative distribution for machine *C1*. The same trend, however, could also be obtained for the other machines (*A1* and *B1*).

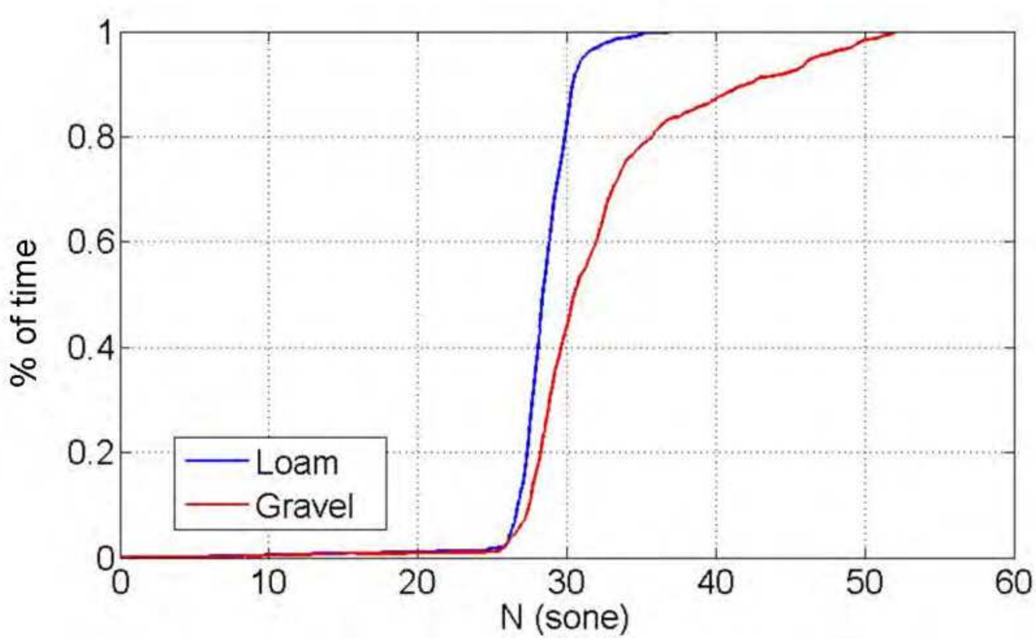

Fig. 6. Loudness cumulative distribution for machine *C1*

This cumulative distribution shows the percentage of time for which a given loudness value (in sone) is not exceeded. The blue line identifies the loudness distribution for the machine working with loam while the red one identifies the loudness distribution for the machine working with gravel. The percentile loudness N_5 can be read at the ordinate point 0.95, N_{10} at the ordinate point 0.90 and N_{95} at the ordinate point 0.05. These two curves have very different gradient, depending on the working conditions (loam or gravel). The curve with lower gradients (gravel) shows that the loudness values are more evenly distributed over time. On the other hand, the noise recordings of the machine working with gravel have always been judged more annoying than those of the machine working with loam. These results seem to confirm some conclusions of previous studies which illustrated how changes of loudness during the considered time frame may be very important in the judgement of annoyance (Genuit, 2006).

4.1.4 Final remarks on the relevance of this investigation

This study provided some fundamental results for the progress of the investigations. Firstly, how to describe the auditory perception of annoyance by means of some objective parameters. Loudness and sharpness are suitable for this purpose and S_5 can be used to better describe the effects on annoyance of the time variability of the noise components at medium-high frequencies.

Secondly, the relevance on the auditory perception of annoyance both of the noise signals overall energy and the frequency distribution. The 400-5000 Hz frequency range, which includes the noise contributions generated by the hydraulic system and the handling of materials, is the most important referring to the annoyance judgements.

Finally, the absolute relevance of the temporal characteristics of these signals in identifying the relationship between machine characteristics/working conditions and auditory perception of annoyance.

4.2 Just noticeable difference in loudness and sharpness

The knowledge of the parameters best correlated to the annoyance sensation is insufficient to develop a methodology able to identify the basic criteria for noise control solutions which guarantee the improvement of the operator comfort conditions. Tiny variations in stimulus magnitude may not lead to a variation in sensation magnitude. In order 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*, should be known for all the parameters of primary interest (Fastl & Zwicker, 2006). JNDs of amplitude and frequency, as well as duration changes of pure/complex tone or broad band noise, have been investigated for decades. Unfortunately, little is known regarding the JNDs of sound quality metrics in real noises (Sato et al., 2007; You & Jeon, 2008). Regarding this a specific investigation was performed by the authors aimed at evaluating the JNDs for the two psychoacoustic parameters describing at best the auditory perception of noise signals at the operator station of compact loaders with respect to the annoyance subjective ratings (loudness and sharpness) (Pedrielli et al., 2008).

4.2.1 Sound stimuli

This investigation involved a binaural noise signal recorded at the operator station of a compact loader of family F in stationary conditions, with the engine running at 2300 rpm. The recorded signal was post-processed following various steps:

- generation of a sound stimulus with the same signal at both ears (diotic stimulus), in order to help listeners to concentrate only on the difference between the sounds having different loudness or sharpness, without being influenced by interaural differences;
- counterbalance of the spectral modifications that occur during playback, depending on the specific sound card and electrostatic headphones used for the listening tests;
- creation of 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 values and 9 with lower loudness values were created. The specific loudness of all these sound stimuli is reported in the left side of figure 7 where the thick line represents the stimulus used as reference in the listening tests.

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 (You & Jeon, 2008), 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 the right side of figure 7 in order to illustrate the filter effect.

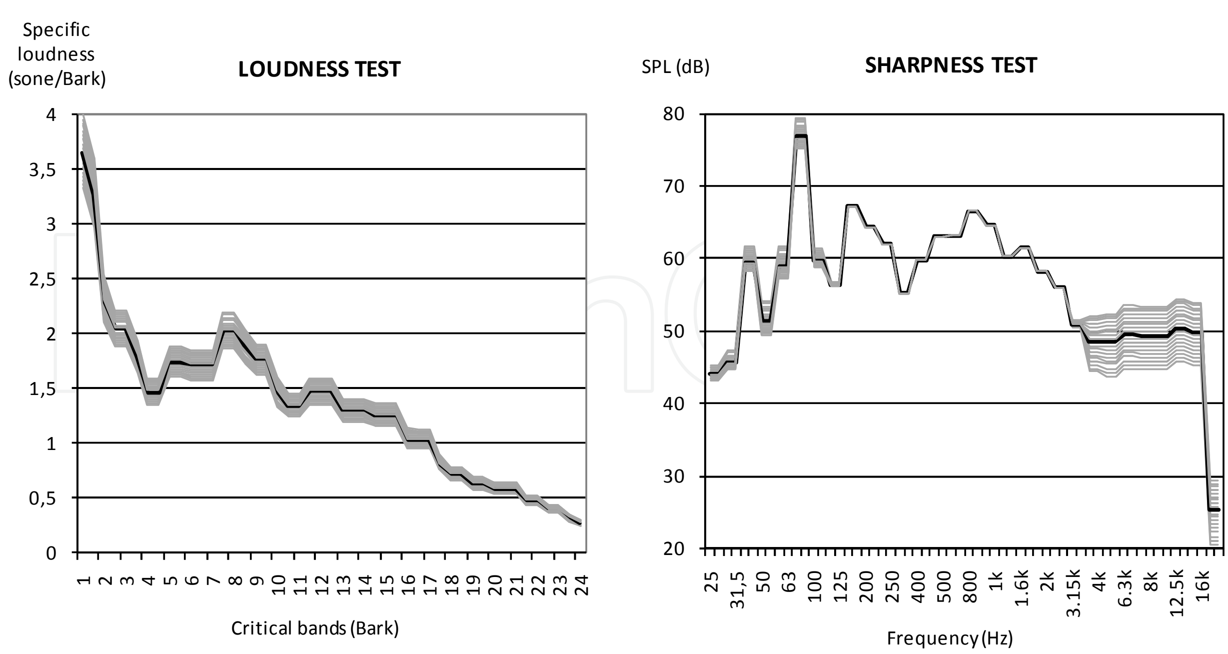

Fig. 7. Specific loudness of the sound stimuli created for the loudness and sharpness JNDs tests

4.2.2 Listening tests

The subjective listening tests were performed following the classical Method of Limits (Gelfand, 1990). According to 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 specific steps. The procedure is repeated several times in subsequent ascending and descending runs.

In our experiments, a total number of six runs (three ascending alternated to three descending runs) were planned for each loudness and sharpness test.

The entire experiment was divided into three test sessions, different from each other as far as the sound pressure levels of the reference stimulus are concerned. In every test session each subject was asked to perform a test to detect firstly 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. 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 was not familiar with the psychoacoustic parameters for which the evaluations were requested (loudness and sharpness).

Table 3 shows the structure of the 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 3. Reference sound stimuli for all the six tests

4.2.3 Results

At the end of the listening tests, the given judgments by each subject were summarised as shown in figure 8.

Referring to the loudness test, the Method of Limits resulted in a range of values in which the second stimulus was louder than the first (reference), a range in which the second was quieter, and a range in which the two sounds appeared to have an equal loudness value. Similar results were found for sharpness test, where "louder" and "quieter" became "higher " and "lower" sharpness, respectively.

The differential threshold (limen) for each subject was estimated once the average upper and lower limens had been defined. The upper limen was halfway between louder/higher and equal judgments, and the lower limen was halfway between quieter/lower and equal judgments. The average limens were obtained by averaging the upper and lower limens across runs. 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 half of this uncertainty interval (Gelfand, 1990).

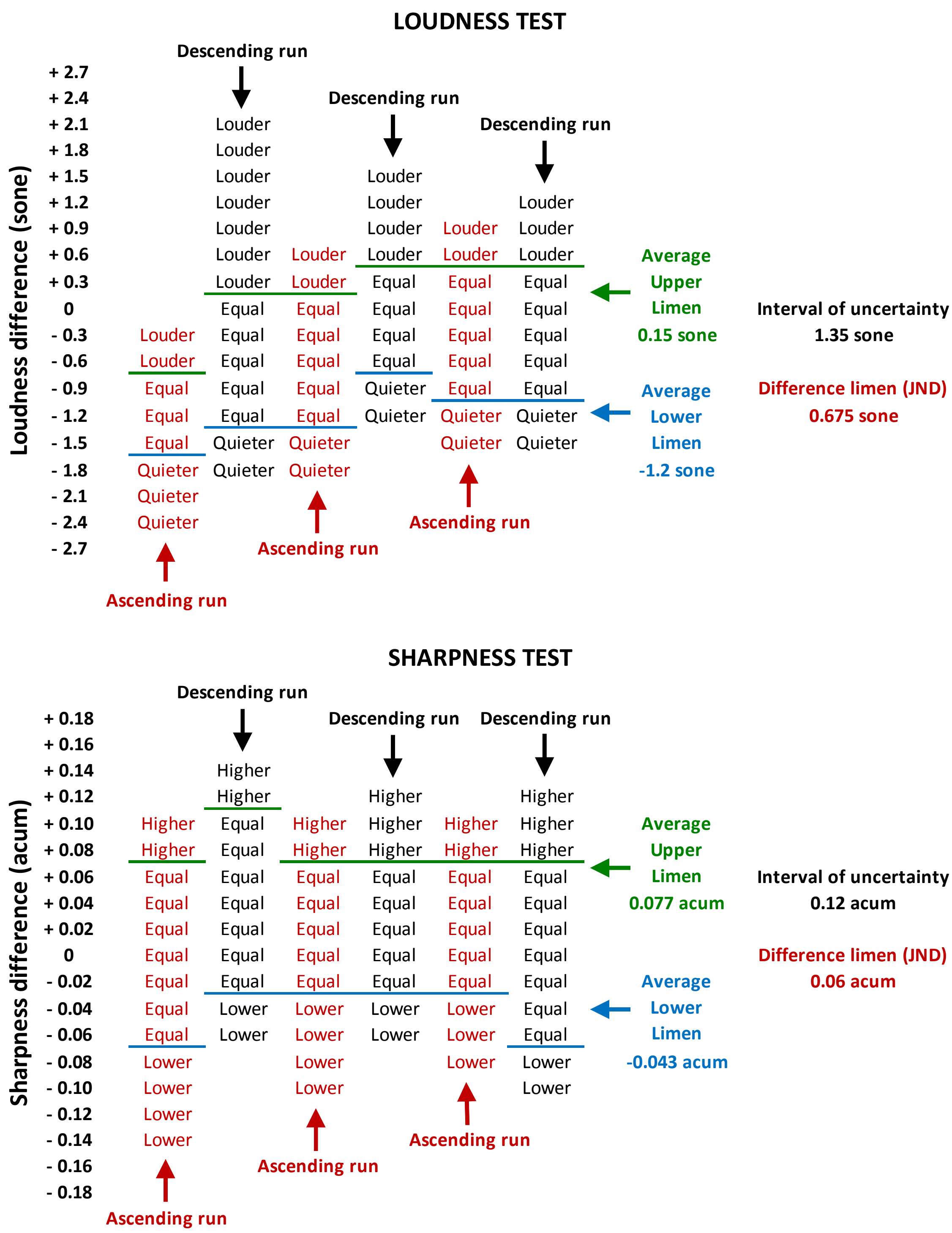

Fig. 8. Judgments given by one subject for the differential thresholds of loudness and sharpness (SPL around 80 dB)

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

Just noticeable differences in loudness

Table 4 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.

	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 4. Just noticeable differences for loudness tests

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.
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.
For this research, the 75° percentile was considered appropriate. An average or median value would not guarantee that the improvement of the operator comfort conditions were extensively appreciated. Consequently, for loaders where the sound pressure levels at the operator position are around 80 dB, the just noticeable difference in loudness is assessed as 0.8 sone.

Just noticeable differences in sharpness

Table 5 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 and only for the 90° percentile.

	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 5. Just noticeable differences for sharpness tests

Also for this psychoacoustic parameter, the just noticeable difference was defined as the minimum variation in sharpness detected by at least 75% of the jury subjects.
Consequently, at the operator station of earth moving machines, the just noticeable difference in sharpness is assessed as 0.04 acum.

4.2.4 Final remarks on the relevance of this investigation

A specific metrics for loudness and sharpness (the two psychoacoustic parameters describing at best the annoyance auditory perception caused by these noise signals) was developed. In order to describe the step size of these parameters that leads to a difference in the hearing sensation of a group of people, a statistical approach was followed. The 75° percentile was considered appropriate; an average or median value, on the contrary, would not guarantee that the improvement of the operator comfort conditions were extensively appreciated. Focusing on the highest presentation level, 75% of subjects perceived a different sensation when sounds had a loudness difference of at least 0.8 sone and a sharpness difference of 0.04 acum.
These values were chosen as JND of loudness and sharpness to be used in the other investigations.

4.3 Active noise control and sound quality improvement

The effectiveness of the active noise control (ANC) approach to strongly reduce the low frequency noise content has already been shown in many applications involving real and simulated experiments (Fuller, 2002; Hansen, 1997, 2005; Scheuren, 2005). As for the specific field of earth moving machines, only a limited bibliography dealing with the ANC approach is available, despite the significant noise contributions at low frequency. On the other hand, the effectiveness of this approach has been evaluated only in terms of reduction of the overall sound pressure level. Taking into account that the noise level reductions are key elements for worker but they are not always related to improvements in sound quality, a study was carried out aimed at complementing the classical evaluations of such an approach with subjective evaluations of the modifications induced by an ANC system with regard to some noise features important to qualify the comfort and safety conditions (Carletti & Pedrielli, 2009).

4.3.1 The implemented ANC system

All the experiments were carried out on a skid steer loader of family B, equipped with lateral windows and door, in the winter version, as shown in figure 9.

Fig. 9. Skid steer loader used for the implementation of the ANC system

In the EMM industry, where the economic constraints are a key element, noise control solutions with a high economic impact associated with the overall cost of the machine are generally not of interest, even if highly technological. Consequently, a cheap and simple single-input single-output system was adopted, with the further limitation that its implementation inside the cab did not require any significant modification in the standard layout of the cab. On the other hand, this choice could be suitable from a technical point of view as inside EMM cabs the volume of interest is very limited and the ANC system must be effective to create a quiet zone only just around the operator's head.

A commercially-available ANC device, following a single channel adaptive feed-forward scheme, was chosen for the tests. This device (1000 Hz sampling frequency) required a reference signal closely related to the primary noise. This synchronism was simply obtained by picking up the impulses from a reflecting strip fixed on the engine shaft of the machine by an optical probe. In such a way the reference signal was not influenced by the control field and the fundamental frequency of the periodic primary noise could be assessed. Based on the reference signal, the ANC device determined the fundamental frequency of the noise, as well as the harmonics to be cancelled. By means of a series of adaptive filters, the output signal was generated and sent to the secondary source.

In order to minimise the economic impact of this implementation, the two loudspeakers of the Hi-Fi system were used as secondary sources. They were fixed to the vertical rods of the cab, at the same height as the operator's head. The error microphone was placed near the operator's head but in such a position that it did not disturb the operator during his work. A low-cost omnidirectional electret condenser microphone with a flat response in the range 40-400 Hz was used. It measured the resulting sound field due to the primary and secondary sources combined.

The control strategy was based on the minimisation of the mean squared value of the sound pressure at the error microphone position (cost function). For this aim, a gradient descendent algorithm was applied in which each controller coefficient was adjusted at each time step in a way that progressively reduced the cost function (filtered-X LMS algorithm) (Nelson & Elliott, 1993). The functional scheme of this ANC system is shown in figure 10.

Two more microphones (Mc) were placed near the operator's ears (by using an helmet worn by the operator) in order to monitor the acoustic field in the area of interest, in real time.

Many experiments were carried out in order to both check the capability of this system to reduce the overall sound pressure level in the volume around the operator's head and track any changes due to engine speed variations fast enough to maintain the control.

Table 6 shows the modifications brought on by the ANC system for three different values of the engine rotational speed (1500, 1800 and 2350 rpm); the second column shows the reduction of the noise component at the engine firing frequency (Δf) and the following two columns show the reduction of the overall levels, linear (ΔL_{eq}) and A-weighted (ΔL_{Aeq}), respectively.

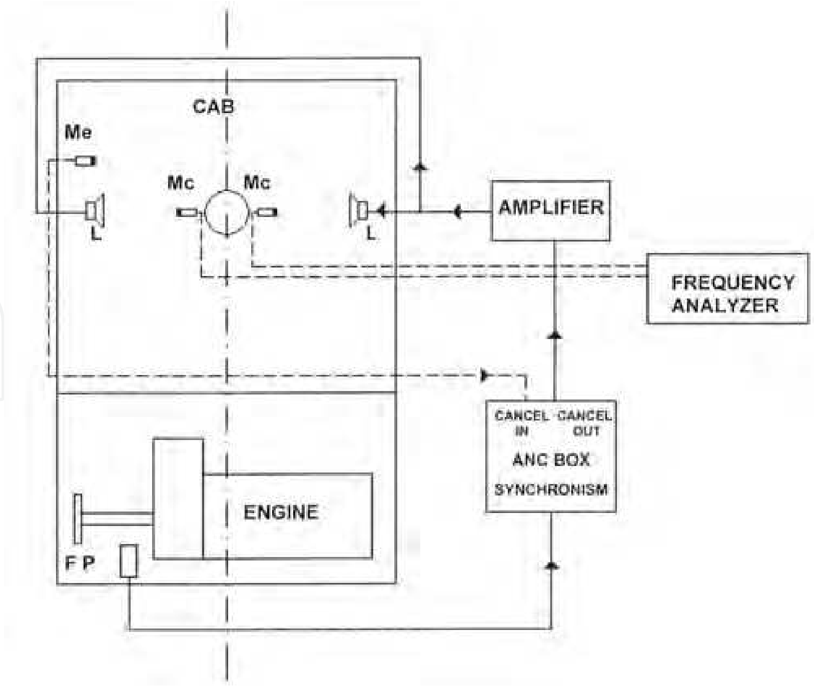

Fig. 10. Layout of the active noise control system. L = loudspeakers, Me = error microphone, Mc = monitoring microphones, FP = photoelectric probe

Rotational speed (rpm)	Δf (dB)	ΔL_{eq} (dB)	ΔL_{Aeq} (dB)
1500	16.8	10.2	2.0
1800	14.8	8.4	1.6
2350	14.9	5.3	0.3

Table 6. Reductions induced by the ANC system at the engine firing frequency (Δf), overall sound pressure level (ΔL_{eq}) and A-weighted overall sound pressure level (ΔL_{Aeq}) for three rpm values

As for the reduction of the overall level, it ranges from 5 to 10 dB and significantly decreases when the engine rotational speed increases: thus the higher the value of rotational speed, the lower the number of tonal components affected by the ANC device. Consequently, a considerable reduction of very few dominant noise components at a low frequency has a small effect on the relevant energetic content of the noise in the frequency range where the system has no influence. This trend is particularly manifest when the effects induced on L_{Aeq} are considered. The reduction of L_{Aeq} is considerably lower than the others (it never exceeds 2 dB) and it turns out to be insignificant at engine speed values higher than 2000 rpm.
From a "physical" point of view, the efficiency of this ANC device decreases when the engine rotational speed increases, the minimum efficiency being reached when the engine speed is at its maximum value (2350 rpm).

4.3.2 Subjective evaluation of the ANC system

Binaural noise recordings were carried out at the operator station of this machine, both with the ANC system activated (C, controlled) and with the ANC system not activated (U, uncontrolled) while the loader was operating in stationary idle conditions with the engine running at 2350 rpm. In such a condition, the ANC had the minimum efficiency and the controlled and uncontrolled noise signals had practically the same energy content at middle-high frequencies but a different distribution of the noise energy at low frequencies, as shown in figure 11. Consequently, subjective tests on controlled and uncontrolled signals would have permitted to check whether this difference, strictly dependent on the ANC action, evoked different subjective reactions despite these two signals had the same L_{Aeq} level.

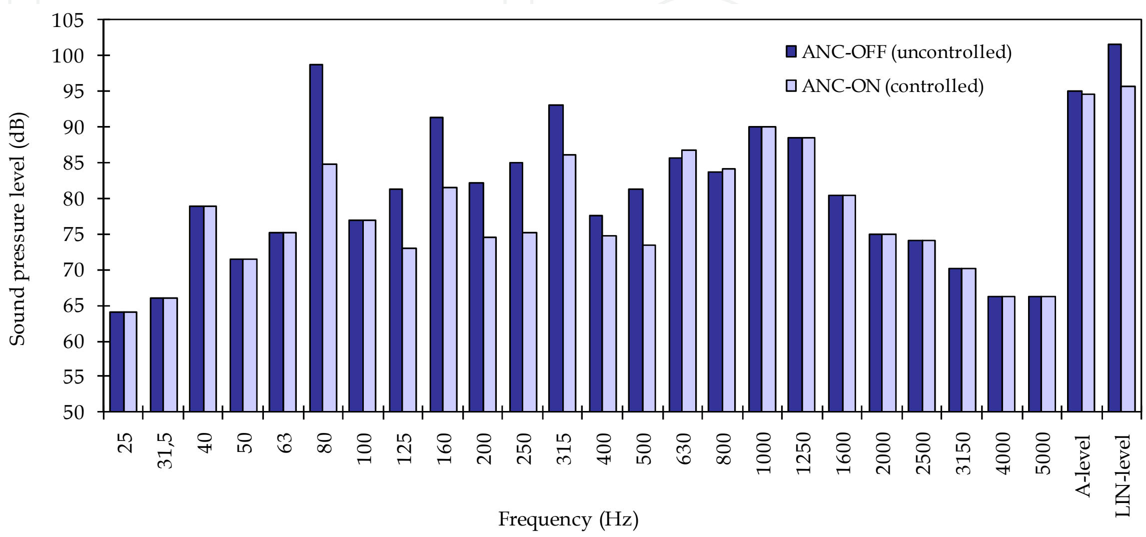

Fig. 11. One-third octave band sound pressure spectra at 2350 rpm with the ANC system on and off

In order to subjectively assess the modifications produced by the ANC system at different levels, both the controlled and uncontrolled sound stimuli were played back at different overall L_{eq} levels, namely 70 dB, 75 dB, and 80 dB. None of these levels actually reproduced the noise at the operator station of the machine (about 20 dB higher). However, these presentation levels were selected mainly to avoid any hazardous hearing effect on the listeners and also because they better highlighted the influence on the auditory perception of specific noise features other than the overall energy content. Table 7 describes the six sound stimuli used in the listening tests.

Sound Stimuli	**Description**	**Overall L_{eq}**	**Overall L_{Aeq}**
U	Original Uncontrolled signal	80 dB	73 dBA
U_{-5}	It has L_{eq} and L_{Aeq} levels 5 dB lower than U	75 dB	68 dBA
U_{-10}	It has L_{eq} and L_{Aeq} levels 10 dB lower than U	70 dB	63 dBA
C	Original Controlled signal	75 dB	73 dBA
C_{+5}	It has L_{eq} and L_{Aeq} levels 5 dB greater than C	80 dB	78 dBA
C_{-5}	It has L_{eq} and L_{Aeq} levels 5 dB lower than C	70 dB	68 dBA

Table 7. Description of the six sound stimuli used in subjective listening tests

As for the subjective evaluation of the modifications produced by the ANC system, particularly interesting was the comparison between uncontrolled and controlled sound stimuli with the same linear or A-weighted overall levels.
Three pairs of sound stimuli had the same linear overall level: U and C_{+5} (80 dB); U_{-5} and C (75 dB); U_{-10} and C_{-5} (70 dB). In each of these pairs both the reduction due to the active noise

control system at the engine firing frequency and its harmonics went with an increase of the noise content at medium-high frequencies, regardless of the overall level.
Only two pairs of sound stimuli had the same A-weighted overall level: U and C (73 dBA); U_{-5} and C_{-5} (68 dBA). In each of these latter pairs the differences are due only to the active noise control system, regardless of the overall level.
The six sound stimuli were arranged in pairs according to the paired comparison procedure and presented to the subjects of the listening jury, tested one at a time. This group of people was formed by eighteen normal-hearing expert operators of earth moving machines, all males aged between twenty-five to fifty years. None of them had previous experience in listening tests but a great experience in using these machines.
After listening to each pair, the subjects were asked to give a rating referring to four different noise features relating to the operator's comfort and working safety conditions: tiredness (T), concentration loss (CL), loudness (L), and booming sensation (B). This rating consisted of a value on a 7-level scale, as shown in figure 12. The meaning of these subjective features was explained to each subject, at the beginning of his listening session. Table 8 details the description given to the subjects for each feature, aimed at reducing the risk of semantic ambiguity.

		A Stimulus				**B Stimulus**		
		Much more than	More than	Slightly more than	Equal to	Slightly more than	More than	Much more than
Features	Tiring	A+++	A++	A+	A=B	B+	B++	B+++
	Causing concentration loss	A+++	A++	A+	A=B	B+	B++	B+++
	Loud	A+++	A++	A+	A=B	B+	B++	B+++
	Booming	A+++	A++	A+	A=B	B+	B++	B+++

Fig. 12. Response scale for each pair of sound stimuli

Features	**ID**	**Description**
Tiring	T	If the noise is heard for at least two hours non-stop, it may cause either tiredness or mental/physical stress
Causing concentration loss	CL	If the noise is heard for at least two hours non-stop, it may cause loss of concentration thus compromising the operator's working tasks
Loud	L	A high level in the sound volume
Booming	B	A buzzing and echoing sound

Table 8. Description of the four subjective noise features

4.3.3 Results of the subjective evaluations

For each feature, the subjective ratings of the six stimuli were computed by pooling the marks into two categories: significant difference (marks "+++" and "++" added together) and no significant difference (marks "+" and "=" added together). The ratings given by the entire listening jury for the significant difference of each feature are shown in table 9. These ratings were normalised with respect to the maximum score that each stimulus could have obtained and then expressed as percentage values.

	Features			
Sound stimuli	**T**	**CL**	**L**	**B**
C_{+5}	85.6 %	81.1 %	88.9 %	44.4 %
U	61.1 %	58.9 %	54.4 %	73.3 %
C	34.4 %	35.6 %	43.3 %	18.9 %
U_{-5}	15.6 %	21.1 %	15.6 %	26.7 %
C_{-5}	4.4 %	4.4 %	6.7 %	1.1 %
U_{-10}	2.2 %	2.2 %	2.2 %	13.3 %

Table 9. Subjective ratings of "significant difference" for the four noise features, in percentage values

The grey area of table 9 shows the subjective ratings of "significant difference" obtained for controlled and uncontrolled signals with the same A-weighted overall sound pressure level: U and C (73 dBA); U_{-5} and C_{-5} (68 dBA). The reductions in the low frequency noise components brought on by the ANC system positively influenced the subjective evaluations in respect of all the noise features when the controlled and uncontrolled signals had significant differences only at low frequencies, no matter what the playback level.

When the subjective ratings of controlled and uncontrolled stimuli with an equal L_{eq} were considered (U and C_{+5} (80 dB); U_{-5} and C (75 dB); U_{-10} and C_{-5} (70 dB)), a different behaviour appeared for the four noise features. As far as the T, CL, and L features are concerned, the subjects always judge the controlled signal worse than the uncontrolled one. This accordance holds at all the different presentation levels, even if the higher the level, the greater the subjective difference between controlled and uncontrolled stimuli. Such results show that the subjective ratings are primarily influenced by the energy content of the noise signal at the medium-high frequencies.

Consequently, the effect of an ANC system in respect of the tiredness, concentration loss and loudness features is negatively judged if the reduction of the low frequency components is accompanied by an increase in the components at high frequencies.

When judging the booming feature, an opposite trend can be noticed: the subjective ratings were always positively influenced by the reduction in the low frequency noise components caused by the ANC system, regardless of the content of the signals at medium-high frequency (stimulus U is more booming than stimulus C_{+5} even if the latter has a higher A-weighted level and then a predominance of the energy content in the medium-high frequency).

4.3.4 Final remarks on the relevance of this investigation

This study showed the feasibility of the ANC approach to improve the sound quality inside loader cabs, provided that the controlled and uncontrolled signals show significant differences only at low frequencies. The sound quality conditions were evaluated by means of subjective evaluations with regards to four different noise features, all related to the operator's comfort and working safety conditions: tiredness (T), concentration loss (CL), loudness (L) and booming sensation (B).

When controlled and uncontrolled signals were forced to have the same overall sound pressure level and then the controlled signal had a higher noise content at the medium-high frequencies, the controlled signal was always judged worse than the uncontrolled one related to concentration loss, tiredness and loudness attributes. Referring to the booming feature, the subjective ratings were always positively influenced by the reduction in the low frequency noise components caused by the ANC system, regardless of the content of the signals at medium-high frequency.

4.4 Annoyance prediction model for loaders

The experience in applying the "product sound quality" approach to the noise signals recorded at the operator station of compact loaders confirmed the effectiveness of this methodology. Besides enlightening the relationship between physical properties of noise signals and auditory perception of some features significant for the acoustic comfort, this approach allowed the authors to identify which noise control criteria could ensure better conditions for the operator.

Unfortunately, this approach requires repeated sessions of jury listening tests which are demanding and time consuming. An annoyance prediction model able to assess the grade of annoyance at the workplace of loaders by using only objective parameters could be an important opportunity for manufacturers and customers. The database of the 62 binaural noise signals recorded at the operator station of several families of compact loaders (see paragraph 2) was therefore used by the authors for this purpose (Carletti et al., 2010a).

4.4.1 Binaural recording and objective characterisations

Based on the results of some other studies (Sato et al., 2007; Kroesen et al., 2008), the following physical parameters were considered relevant for this investigation:

- the overall sound pressure levels: L_{eq}, L_{Aeq}, L_{Ceq}, L_{Peak} ;
- the percentile values of the sound pressure levels (Lp_5, Lp_{10}, Lp_{50}, Lp_{90}, Lp_{95});
- the overall values of loudness N, sharpness S, roughness and fluctuation strength;
- the percentile values of loudness (N_5, N_{10}, N_{50}, N_{90}, N_{95}) and sharpness (S_5, S_{10}, S_{50}, S_{90}, S_{95}).

These parameters were estimated for the complete data set of noise stimuli, for right and left channels separately. Then the stimulus with the highest Pearson correlation coefficient with respect to the subjective annoyance score was considered for subsequent analyses.

4.4.2 Listening tests and subjective annoyance scores

The database of the 62 binaural noise signals was divided into nine different groups. For each noise group the subjective assessment of annoyance was obtained by means of subjective listening tests carried out according to the paired comparison procedure.

80 normal-hearing subjects (60 males and 20 females) aged between 24 and 50 were involved in the various listening tests. None of them was familiar with earth moving machines but all of the subjects had some knowledge in acoustics and some of them had also prior experience in listening tests. In addition, for each of the noise groups, the number of subjects involved in the test was never lower than 15, with the only exception of group 6 test which involved 9 subjects only. The overview of all the binaural noise stimuli belonging to each noise group and the percentage values of the subjective annoyance scores obtained for each of them are shown in table 10.

Group 1 10 binaural signals recorded from 5 loaders of family A during the working cycle with loam (L) and gravel (G)										**Group 2** 5 binaural signals from 5 loaders of family A during the simulated work cycle (S)				
$A1_L$	$A2_L$	$A3_L$	$A4_L$	$A5_L$	$A1_G$	$A2_G$	$A3_G$	$A4_G$	$A5_G$	$A6_S$	$A7_S$	$A8_S$	$A9_S$	$A10_S$
15.7	71.1	27.9	50.4	21.3	69.3	48.6	50.5	94.6	50.5	66.7	51.7	15.8	27.5	88.3
Group 3 10 binaural signals recorded from 5 loaders of family B during the working cycle with loam (L) and gravel (G)										**Group 4** 5 binaural signals from 5 loaders of family B during the simulated work cycle (S)				
$B1_L$	$B2_L$	$B3_L$	$B4_L$	$B5_L$	$B1_G$	$B2_G$	$B3_G$	$B4_G$	$B5_G$	$B6_S$	$B7_S$	$B8_S$	$B9_S$	$B10_S$
18.5	18.5	57.0	47.9	13.7	75.9	64.7	86.3	65.4	52.1	55.0	30.0	70.0	65.8	29.2
Group 5 10 binaural signals recorded from 5 loaders of family C during the working cycle with loam (L) and gravel (G)										**Group 6** 5 binaural signals from 5 loaders of family C during the simulated work cycle				
$C1_L$	$C2_L$	$C3_L$	$C4_L$	$C5_L$	$C1_G$	$C2_G$	$C3_G$	$C4_G$	$C5_G$	$C6_S$	$C7_S$	$C8_S$	$C9_S$	$C10_S$
12.1	26.0	50.0	25.5	44.4	83.4	60.0	68.4	63.9	66.2	33.3	55.8	88.3	36.7	35.8

Group 7 6 binaural signals from 3 loaders of family D during the work cycle with gravel (G) and loam (L)						**Group 8** 6 binaural signals from 3 loaders of family E during the work cycle with gravel (G) and loam (L)						**Group 9** 5 binaural signals from 5 loaders of family F recorded in stationary conditions				
$D1_G$	$D2_G$	$D3_G$	$D1_L$	$D2_L$	$D3_L$	$E1_G$	$E2_G$	$E3_G$	$E1_L$	$E2_L$	$E3_L$	F1	F2	F3	F4	F5
43.2	77.9	98.9	18.9	22.1	38.9	35.6	77.8	93.3	6.7	46.7	40.0	77.9	76.5	70.6	2.9	22.1

Table 10. Groups of noise stimuli and percentage values of subjective annoyance scores

4.4.3 Multiple regression analysis

The first six groups of noise stimuli were used to develop the annoyance prediction model while the last three were kept aside to validate it.

In order to reach the proposed target, multiple regression analysis was chosen as this technique is the most commonly used for analysing multiple dependence between variables and also because the theory is well developed (Kleinbaum et al., 2007).

In this investigation, the Stepwise selection method was firstly applied to each group of noise stimuli in order to identify the smallest set of independent variables which best explained the variation in the subjective annoyance scores (Lindley, 1968). In this respect, the score from subjective listening tests was entered as "dependent variable" and all the objective parameters, considered to be relevant for this investigation, were used as "independent variables". The results obtained for the six groups are shown in table 11.

Noise group	1	2	3	4	5	6
Predictor variables	*N*	S_{90}, *Peak*, N_{50}	N_{10}, *Peak*	*Peak*, S_5	N_{10}, *Peak*, N_{50}	N_{95}, S_{95}
R^2	0.63	1.00	0.95	1.00	0.95	1.00
Adjusted R^2	0.58	1.00	0.94	1.00	0.93	1.00

Table 11. Results of the "Stepwise" selection method applied to the six noise groups

In this table, the parameter R^2 is the square value of the correlation coefficient between the subjective scores and the predicted values of the annoyance. It quantifies the suitability of the fit of the model and shows the proportion of variation in the subjective scores which is explained by the set of the identified parameters. In addition, the Adjusted R^2 values, which takes into account the number of variables and the number of observations, were calculated in order to give a most useful measure of the success of the prediction when applied to real world.

For each noise group the variables selected by the Stepwise method account for more than 93% of the variation in the subjective scores, with the only exception of group 1. In addition, the set of the physical parameters which represent loudness, sharpness and peak level are very often included in the model, independently from the specific noise group. On the other hand, all the parameters which reflect the same quantity such as N, N_{10}, N_{50} and N_{95} for loudness, or S_5, S_{90} and S_{95} for sharpness are strongly correlated among each other.

Consequently, in order to identify a common set of predictor variables for each of the six noise groups, further analyses were carried out by substituting some of the parameters shown in table 11 with others reflecting the same acoustic features. The multiple regression analysis was then repeated on the six groups with the "Enter" variable selection method, that is forcing the choice of the set of predictor variables among (Peak, N, S_5), (Peak, N, S_{90}), (Peak, N, S_{95}), (Peak, N_{10}, S_5), ... etc...

The set of predictor variables which led to the highest R^2 values for the correlation between predicted and observed annoyance scores was (Peak, N_{50}, S_5). The multiple regression equations for this set of parameters are shown in table 12.

Predictor variables	Noise group	Multiple Regression Equation	R^2	Adjusted R^2
Peak, N_{50}, S_5	1	$Y = -9.310 + 0.057 \cdot Peak + 0.184 \cdot N_{50} + 0.216 \cdot S_5$	0.79	0.69
	2	$Y = -5.512 + 0.039 \cdot Peak + 0.296 \cdot N_{50} - 3.703 \cdot S_5$	0.99	0.97
	3	$Y = -5.322 + 0.038 \cdot Peak + 0.057 \cdot N_{50} + 0.412 \cdot S_5$	0.89	0.83
	4	$Y = -18.214 + 0.061 \cdot Peak + 0.018 \cdot N_{50} + 9.628 \cdot S_5$	1.00	1.00
	5	$Y = -4.241 + 0.030 \cdot Peak + 0.046 \cdot N_{50} + 0.289 \cdot S_5$	0.96	0.94
	6	$Y = 6.971 - 0.012 \cdot Peak + 0.312 \cdot N_{50} - 11.350 \cdot S_5$	0.89	0.55

Table 12. Results of the "Enter" selection method applied to the six noise groups

For each noise group this set of variables accounts for at least the 89% of the variation in the subjective scores, with the only exception of noise group 1. In addition, the big difference between R^2 and Adjusted R^2 values for group 6 takes into account the limited number of subjects involved in this test.
These results, which might be referred to as compromise solutions are only slightly worse than the best solutions obtained following the “Stepwise” variable selection method.

4.4.4 Predicted annoyance (P.A.)

In order to identify the best annoyance model among the regression equations obtained for the six different noise groups, and listed in table 12, each regression equation was applied to all the other five groups and for each equation the predicted annoyance values were calculated. Then the correlation between these predicted annoyance values and the observed subjective ratings was evaluated for each noise group: the better the correlation the higher the R^2 value. In such a way the best annoyance prediction model was the one that gave the maximum sum of R^2 over all the noise groups except for the one from which that model was issued.
According to this criterion, the regression equation referred to group 3 was the best and was chosen as the prediction model to assess the noise annoyance at the workplace of compact loaders (P.A. = Predicted annoyance) :

$$P.A. = - 5.322 + 0.038 \cdot Peak + 0.057 \cdot N_{50} + 0.412 \cdot S_5 \quad (9)$$

4.4.5 Validation of the model

In order to verify whether this prediction model is applicable to noise signals other than those from which the equation was derived, the noise groups 7, 8, and 9 were then involved in the analysis.
Referring to noise signals of groups 7 and 8, the model gave predicted annoyance values that were significantly correlated with the subjective scores (correlation coefficients 0.95 and 0.96). Referring to group 9, it included noise signals recorded in stationary conditions and then with characteristics significantly different from those from which the model was issued (working conditions). These signals had sound pressure levels and loudness values higher than those of all the other signals, approximately 20 dB and 70 sone, respectively. Despite these differences, also this group showed a quite good correlation ($r = 0.85$ corresponding to a significance level of 5.6 percent).
However, considering that subjective listening tests were performed on each group separately, the annoyance scores could not be compared among different groups. For this reason, a further validation was deemed necessary. New subjective listening tests involving all the sound stimuli referred to a certain family of compact loaders (independently from the operating condition of the machine) were carried out according to the experimental procedures described in paragraph 3.3. The results are shown in table 13.
The comparison between the predicted values of annoyance and the subjective annoyance scores obtained by these new listening tests showed again a very good correlation. Figure 13 shows the predicted annoyance (P.A.) values against the observed values for the three groups of signals. The high values of the squared correlation coefficient (R^2) (0.898, 0.909, 0.934, respectively) confirm the suitability of the fit of this model.

Group A 15 binaural noise signals recorded from 10 loaders of family Aduring the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)														
$A1_L$	$A2_L$	$A3_L$	$A4_L$	$A5_L$	$A1_G$	$A2_G$	$A3_G$	$A4_G$	$A5_G$	$A6_S$	$A7_S$	$A8_S$	$A9_S$	$A10_S$
15.7	64.9	26.6	46.5	20.7	85.0	66.7	68.4	99.2	68.4	54.3	39.3	3.5	15.1	75.9
Group B 15 binaural noise signals recorded from 10 loaders of family Bduring the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)														
$B1_L$	$B2_L$	$B3_L$	$B4_L$	$B5_L$	$B1_G$	$B2_G$	$B3_G$	$B4_G$	$B5_G$	$B6_S$	$B7_S$	$B8_S$	$B9_S$	$B10_S$
34.4	34.4	72.5	63.5	29.6	84.5	73.4	94.8	74.1	60.9	29.7	9.0	42.2	38.7	8.3
Group C 15 binaural noise signals recorded from 10 loaders of family Cduring the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)														
$C1_L$	$C2_L$	$C3_L$	$C4_L$	$C5_L$	$C1_G$	$C2_G$	$C3_G$	$C4_G$	$C5_G$	$C6_S$	$C7_S$	$C8_S$	$C9_S$	$C10_S$
30.2	45.0	70.6	44.4	64.7	89.6	64.6	73.5	68.8	71.1	13.6	29.6	52.9	16.0	15.4

Table 13. Subjective annoyance scores (% values) for tests on loaders of family A, B, and C

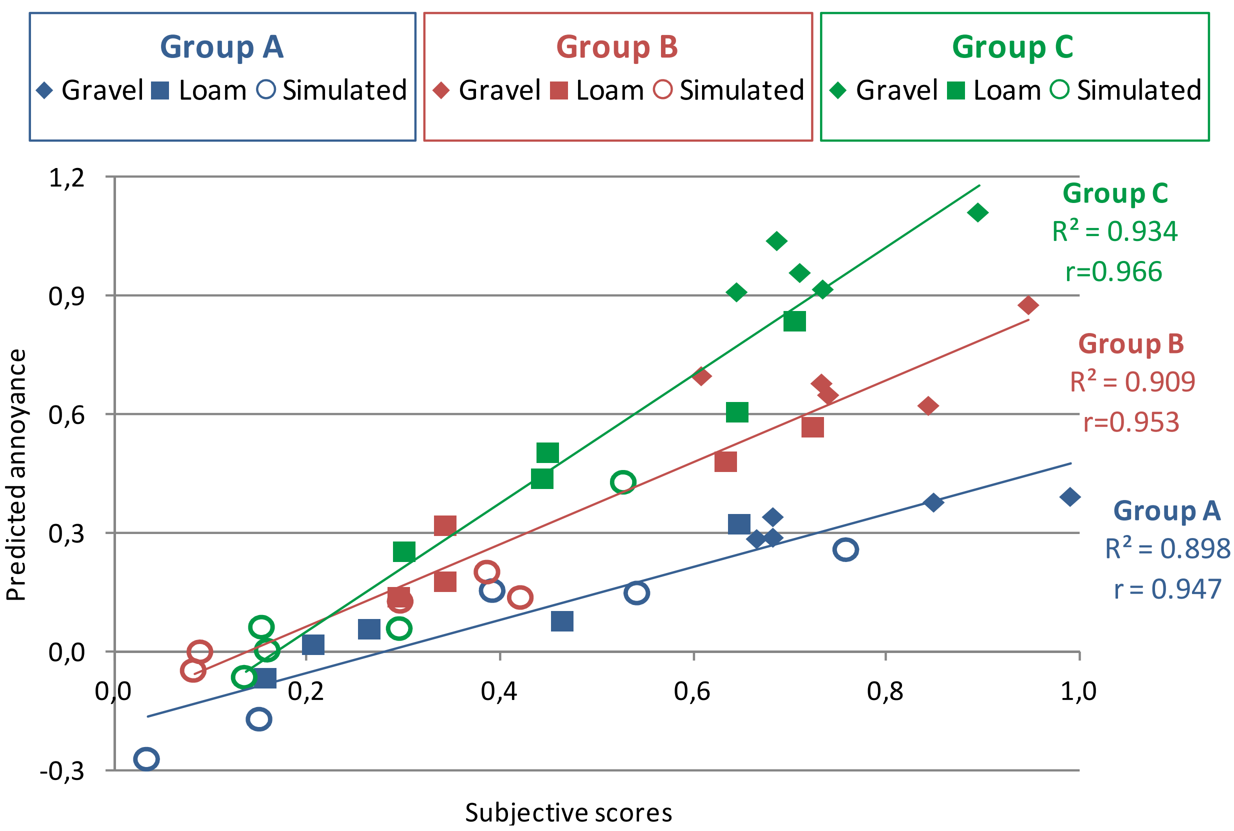

Fig. 13. Comparison between predicted and observed values of annoyance (subjective scores) for the three groups of signals (A, B, C)

4.4.6 Final remarks on the relevance of this investigation

The prediction model was developed on the basis of a huge amount of binaural noise signals recorded at the operator position of several families of loaders. Its regression equation :

$$P.A. = -5.322 + 0.038 \cdot Peak + 0.057 \cdot N_{50} + 0.412 \cdot S_5 \quad (10)$$

could provide an alternative and simpler way for manufacturers and customers to assess the grade of annoyance at the workplace of any loader. This model, indeed, intrinsically reflects the main results of the sound quality approach but it is obtained by means of objective parameters only.

5. Conclusion

This chapter collects the main results of the research performed by the authors in the last five years in order to identify a methodology that is able to establish the basic criteria for noise control solutions which guarantee the improvement of the operator comfort conditions. All the investigations were carried out on compact loaders and permitted to collect the following main results.

Auditory perception of annoyance (see paragraph 4.1)

This study was aimed at better understanding the relationship between the multidimensional characteristics of the noise signals in different working conditions and the relevant auditory perception of annoyance. It highlighted that sharpness and loudness are suitable for this purpose, that the 400-5000 Hz frequency range - which includes the noise contributions generated by the hydraulic system and the handling of materials - is the most important referring to the annoyance judgements and that the temporal characteristics of the signals play an important role. The sharpness fifth percentile S_5 can be used to better describe the effects on annoyance due to the time variability of the noise components at medium-high frequencies.

Just noticeable difference in loudness and sharpness (see paragraph 4.2)

This study was aimed at evaluating the minimum differences in loudness and sharpness which are subjectively perceived (just noticeable differences, JND). This information is necessary to develop the specific metrics because tiny variations in stimulus magnitude may not lead to a variation in sensation magnitude. It highlighted that the just noticeable difference in loudness becomes greater as the overall sound pressure level of the signal increases while the just noticeable difference in sharpness has very small variations related to the overall level. Referring to sound stimuli with sound pressure levels around 80 dB, 75% of subjects perceived a different hearing sensation when sounds had a loudness difference of at least 0.8 sone and a sharpness difference of 0.04 acum. This step size was chosen as the JND of loudness and sharpness for all the other investigations.

Effectiveness of an active noise control (see paragraph 4.3)

This study was aimed at verifying the feasibility of a simple active noise control (ANC) architecture. The sound quality conditions were evaluated by means of subjective tests with regards to four different noise features, all related to the operator's comfort and working safety conditions: tiredness, concentration loss, loudness and booming sensation. It highlighted that the effect on the subjective responses of a selective reduction, due to the active noise control system, becomes significant when comparing sounds with the same band levels except for that at the controlled frequency (engine firing frequency, in this case). Therefore in order to improve the operator's comfort and his working safety it would be more effective if the spectral modification produced by an active noise control was associated with a level control in the medium-high frequency range.

Annoyance prediction model (see paragraph 4.4)

This study was aimed at developing a prediction model able to evaluate the grade of annoyance at the workplace of compact loaders by using objective parameters only. This model could provide an alternative and simpler way for manufacturers and customers to assess the grade of annoyance at the workplace of all loaders as it intrinsically reflects the main results of the sound quality approach but it depends on objective parameters only.

This model was developed by multi regression analysis thanks to the great amount of the available jury test results and the relevant database of binaural noise signals referred to this kind of machine. It included objective parameters *Peak*, N_{50} and S_5 with regression coefficients which best explained the variations of the subjective annoyance scores for all the noise groups used in the developing process. The validation process confirmed a very good correlation between the predicted annoyance values and the subjective ratings resulting from jury tests.

Further investigations are in progress, aimed at applying numerical optimisation methods to these noise signals in order to analytically identify the changes in the frequency content which lead to a simultaneous reduction of loudness and sharpness values. As a consequence of the high correlation of these parameters with the subjective perception of annoyance, the noise modifications able to simultaneously reduce these parameters seem to be a promising approach for improving the acoustic comfort at the operator position. The preliminary results of this study have already been published (Carletti et al., 2010b).

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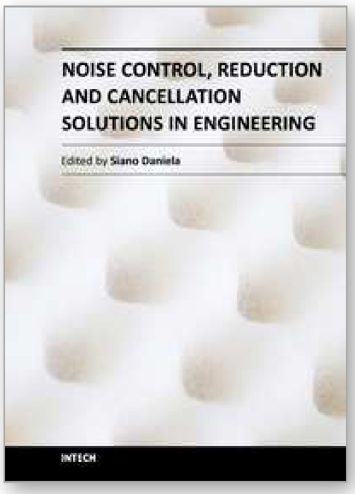

Noise Control, Reduction and Cancellation Solutions in Engineering
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Noise has various effects on comfort, performance, and human health. For this reason, noise control plays an increasingly central role in the development of modern industrial and engineering applications. Nowadays, the noise control problem excites and attracts the attention of a great number of scientists in different disciplines. Indeed, noise control has a wide variety of applications in manufacturing, industrial operations, and consumer products. The main purpose of this book, organized in 13 chapters, is to present a comprehensive overview of recent advances in noise control and its applications in different research fields. The authors provide a range of practical applications of current and past noise control strategies in different real engineering problems. It is well addressed to researchers and engineers who have specific knowledge in acoustic problems. I would like to thank all the authors who accepted my invitation and agreed to share their work and experiences.