Subjective evaluation of a simple active noise control system mounted inside an earth moving machine cab

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A series of experiments were carried out in order to verify the feasibility of an active noise control (ANC) approach to improve the acoustic comfort at the operator's station of a compact loader. For this kind of application expensive noise control solutions would be too expensive for the market and therefore unsuitable. Hence, a very simple active noise control layout using a single channel feed-forward scheme was used. Its capability to reduce the dominant low frequency noise components and the overall level within the space where the operator's head is located during his/her work was experimentally verified. Then, the modifications caused by this ANC system were subjectively evaluated with regards to some important noise features (tiredness, concentration loss, loudness and booming sensation) in order to qualify comfort and working safety conditions for the operator.

Primary subject classification: 53.2; Secondary subject classification: 38.2

1 INTRODUCTION

Nowadays, the improvement of the acoustic comfort at the operator's station of earth moving machines (EMMs) has become a key issue. In fact, besides the European Directives which have been limiting the airborne noise emissions produced by these machines for over twenty years, the 2003/10/EC Directive[1] on health and safety requirements for noise exposure at work is currently being transposed to all the European Member States. Consequently, national legislations have specified lower noise limits for workplaces.

On the other hand, the market requests are more and more oriented to machines with high-level performance and this trend is making noise one of the key factors to face the strong competition.

In this context, EMM manufacturers have primarily addressed their efforts to comply with standards and then both the A-weighted sound power level emitted by these machines and the A-weighted sound pressure level at the operator's station have been significantly reduced below the limits, with the A-weighted sound pressure levels generally lower than 85 dBA.

Unfortunately, although allowing manufacturers to comply with the legislative requirements, in many cases this approach did not lead to successful results in terms of acoustic comfort perceived by the operator. Recent research, indeed, showed that even if some machines met the noise limits issued by legislation, they still elicited negative responses in terms of annoyance and interference with activities, which both decrease work performance[2]. The reason is that the A-weighted parameter, on its own, is not always adequate to appropriately describe auditory perception[3].

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[4–11]. In specific fields like in automobiles, a rich bibliography shows the efficiency of multi-input multi-output ANC architectures to strongly reduce the A-weighted level both at driver and passenger seats, simultaneously[12–16].

As for the specific field of EMM noise, however, only a limited bibliography dealing with the ANC approach is available[17–22]. In addition, almost all papers describe the simulation of the ANC process but only few real case histories are reported.

The current study reports the results of the application of an active noise control system to an earth moving machine, with the purpose to verify whether the modifications caused by the system are positively judged by the machine operators.

In the EMM industry, where the economic constraints are a key element, noise control solutions with a high economic impact associated with the

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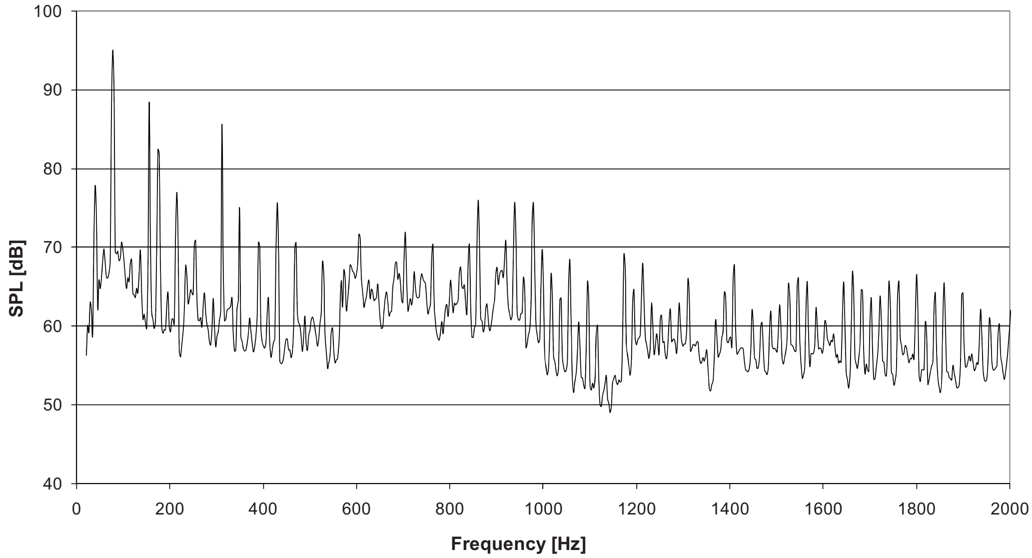

Fig. 1—FFT spectrum measured at the operator station of an earth moving machine, with the engine idling at 2350 rpm.

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 here, with the further limitation that its implementation inside the cab did not have to require any significant modification in the standard layout of the cab. On the other hand, this choice might have also been suitable from a technical point of view: inside EMM cabs, in fact, 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.

The subjective evaluation of this ANC system was carried out by means of specific laboratory listening tests where a group of EMM operators had to judge the modifications caused by the ANC device with regards to some important features (tiredness, concentration loss, loudness and booming sensation) in order to qualify comfort and working safety conditions for the operator.

2 THE ANC SYSTEM

2.1 Implementation of the ANC System Inside the Machine Cab

In normal working conditions, the main periodic noise components at the operator station of a construction machine are all strictly related to the engine rotational speed, with the fundamental frequency within the range 25–50 Hz and the highest noise levels linked to its first ten harmonics. These components are generally due to the engine injection cycles (2 or 3 per revolution depending on the number of cylinders), to the cooling system (fan with 6-8 blades) and to the hydraulic system (pumps with 8-12 gear teeth). Consequently, with the only exception of the peaks at the highest harmonics of the hydraulic system, all the dominant noise components can be affected by an ANC device. Fig. 1 shows an example of a FFT spectrum measured at the operator station of an earth moving machine, with the engine idling at 2350 rpm.

All the experiments were carried out on a skid steer loader (see Fig. 2) equipped with lateral windows and door, in the winter version. The choice of this kind of EMM was determined by the fact that this machine is widely used not only for outdoor works but also in the activities of building construction and restoration. In addition, it is one of the most critical EMMs 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 isolated from the outside due to problems with overheating.

A commercially-available ANC device, following a single channel adaptive feed-forward scheme, was chosen for the tests. This choice was determined for two main reasons. Firstly, it would have met the

Fig. 2—Skid steer loaders.

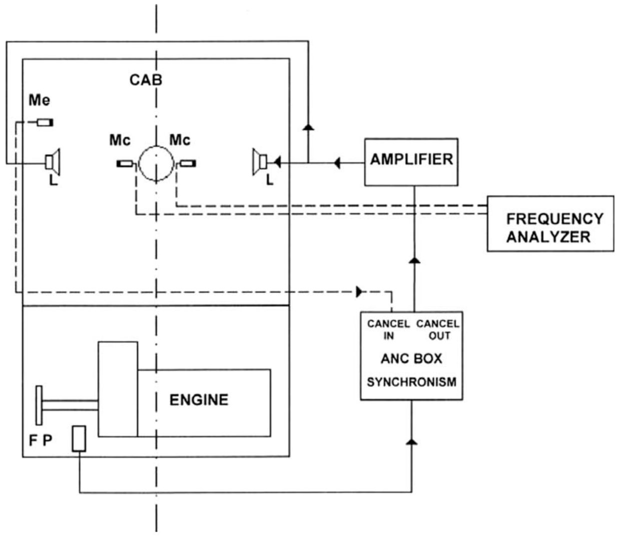

Fig. 3—Layout of the active noise control system. L = loudspeakers, Me=error microphone, Mc=monitoring microphones, FP=photoelectric probe.

manufacturer expectations in terms of low costs and ease of implementation. Secondly, it could have been effective to create a quiet zone around the operator's head, due to the extremely limited size of the space of interest[23,24]. The internal overall volume of the cab, indeed, is almost 1 m^3 and the average dimension of the area in which the operator's head and torso are located, is $0.8 \times 0.8 \times 1$ m.

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 minimize 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/her 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 minimization 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).

The functional scheme of the ANC system used is shown in Fig. 3. Two more microphones (Mc) were placed at the operator's ear's position (by using an helmet worn by the operator) in order to monitor the acoustic field in the area of interest, in real time.

Table 1—Reductions induced by the ANC system at the engine firing frequency (Δ_f), overall sound pressure level (ΔL_{eq}) and A-weighted overall sound pressure level (ΔL_{Aeq}) for three rpm values.

Rotational speed (rpm)	Δ_f (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

2.2 First Experiments

Many experiments were carried out in order to both check the capability of this system to reduce the overall sound pressure level of the volume around the operator's head and track any changes due to engine speed variations fast enough to maintain the control. Some results of these experiments are shown in Table 1 where the modifications brought on by the ANC system for three different values of the engine rotational speed (1500, 1800 and 2350 rpm) are reported. The first column shows the reduction of the noise component at the engine firing frequency (Δ_f); the second and third columns show the reduction of the overall levels, linear (ΔL_{eq}) and A-weighted (ΔL_{Aeq}), respectively.

As for the reduction of the overall level, it ranges from 5 to 10 dB which significantly decreases as 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. Only for low rotational speed values, indeed,

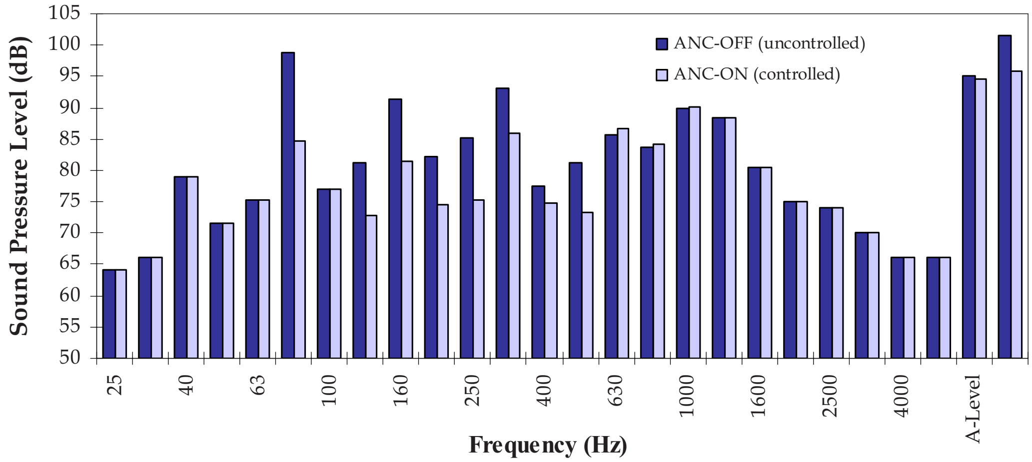

Fig. 4—1/3 octave band sound pressure spectra with the ANC system on and off.

the ANC system is able to reduce the noise components which have a remarkable effect in terms of A-weighted level.

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).

3 SUBJECTIVE EVALUATION OF THE ANC SYSTEM

A correct subjective evaluation of sound events that originate from several sources spread out in space requires binaural recordings, binaural signal processing and binaural listening tests. Therefore binaural noise recordings were carried out at the operator's station of the tested machine by using a dummy head and torso (Cortex MK1). The reason for this choice was that a dummy head and torso has the advantage of having a high repeatability, still ensuring that the sound waves reaching the head undergo the same transmission on their way to the ear canals as if they were reaching a real listener[25].

The test site consisted of a wide open area (concrete surface) with a very low background noise. The measurements were taken on the skid steer loader both with the ANC system activated (C, controlled) and with the ANC system not activated (U, uncontrolled) while the machine was operating in stationary idle conditions with the engine running at 2350 rpm. Figure 4 shows the 1/3 octave band sound pressure spectra at the operator's ears' position, obtained at this engine speed with the ANC system off and on.

When the ANC device is not activated, the main contribution to the overall sound pressure level is mainly given by the noise component at the engine firing frequency (80 Hz); when it is activated, this noise component is greatly reduced (about 15 dB) and a further reduction (10 to 4 dB) can also be noticed for the first subsequent harmonics of the engine fundamental frequency. The overall sound pressure level is reduced of about 5 dB while no significant modifications of the A-weighted level are obtained.

The choice of the operating condition where the ANC has the minimum efficiency (2350 rpm) was determined by the fact that in such a condition 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. This difference, strictly dependent on the ANC action, could evoke different subjective reactions even if the two noise signals have the same L_{Aeq} level.

Binaural recordings need to be processed before being played back in binaural listening tests. In general, a correct playback of these signals can be performed by headphones or by loudspeakers in an adequate test environment. Both approaches are in use but listening by headphones ensures that the sound picked up in one ear is only reproduced in that ear and does not require the implementation of cross-talk cancellation between loudspeakers[25]. On the other hand, listening by headphones reduces the ability of a correct spatial sound localization. For sounds recorded in earth moving machines this effect is not so important as the frequency content is gathered in the medium-low frequency range that is not directional.

In this investigation, subjective listening tests were undertaken in a quiet environment by means of high-quality electrostatic headphones (STAX signature SR-404) with a flat response in the 40−40000 Hz frequency range. The sound stimuli used in the listening tests derived from the aurally adequate process of the original noise recordings. This process allows for the fact that[26]:

— the headphones are not exactly positioned at the same location as the microphones;

Table 2—Description of the six sound stimuli used in subjective 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

— the dynamics of ear canals are modified by their closeness to the headphones;
— the headphones themselves have specific spectral characteristics that must be taken into account.

In order to subjectively assess the modifications produced by the ANC system at different levels, both the aurally-adequate sound stimuli (controlled and uncontrolled) 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's station of the machine, which is 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. The six sound stimuli used in the listening tests are described in Table 2.

As for the subjective evaluation of the modifications produced by the ANC system, particularly interesting is the comparison between uncontrolled and controlled sound stimuli with the same linear or A-weighted overall levels.

Three pairs of sound stimuli have 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 go with an increase of the noise content at medium-high frequencies, regardless of the overall level. This behavior is shown in Fig. 5 for the U and C_{+5} sound stimuli.

Only two pairs of sound stimuli have 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. This behaviour is shown in Fig. 6 for the U and C sound stimuli.

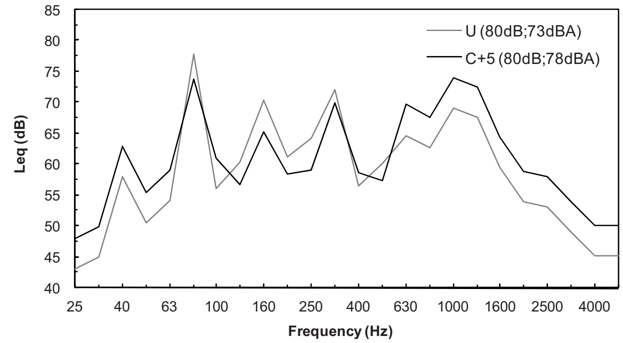

Fig. 5—Differences for the 1/3 octave band sound pressure spectra for stimuli with equal L_{eq} level.

3.1 Subjective Listening Tests

Blauert[27] indicates that a general definition of measurement comprises any assignment of numbers to objects in such a way that relations between the numbers reflect relations between the objects. Psychoacoustic judgments can be subsumed under such a general concept of measurement, provided that judgments map relations between attributes of percepts in a quantitative way. In experimental procedures which render this kind of results, the subjects act as a measurement device to measure their own percepts.

The results of tests with subjects tend to show a higher variance than usually encountered with instrumental measurements. Anyway, the use of appropriate psychometric procedures tends to limit this effect.

For the assessment of very similar sounds a direct estimation of their sound quality is not suitable especially for untrained subjects. Among the psychophysical procedures, a relative comparison between sounds represents a much easier task for the subject and makes the detection of the difference among the sound stimuli easier to assess[28]. For this reason, in this investigation the six sound stimuli were arranged in pairs (A stimulus—B stimulus) according to the paired

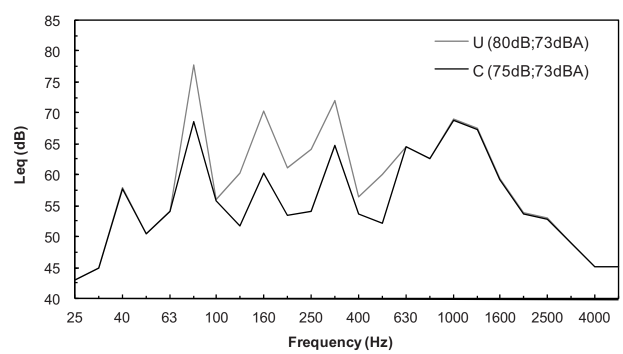

Fig. 6—Differences for the 1/3 octave band sound pressure spectra for stimuli with equal L_{Aeq} level.

A-B	A-C	A-D	A-E	A-F
	B-C	B-D	B-E	B-F
		C-D	C-E	C-F
			D-E	D-F
				E-F

Fig. 7—Combinations of 6 items taken 2 at a time.

comparison procedure. In this method, each sound stimulus is directly compared to all the others and the subject is asked to give his/her judgment, after listening to each pair.

The 15 pairs for which the judgment has to be given are obtained by combining 6 items (the sound stimuli) taken 2 (a pair) at a time. If the 6 sound stimuli are identified as A, B, C, D, E, F, the 15 pairs are those shown in Fig. 7.

Each pair consisted of two signals both lasting 4 s, including a 0.15 s fade-in, and separated by 1 s of silence. The pairs were presented to a listening jury formed by eighteen normal-hearing expert operators of earth moving machines. This group of people had no previous experience in listening tests; they were all males aged between twenty-five to fifty years and each tested one at a time.

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). The meaning of these subjective features was explained to each subject, at the beginning of his listening session. Table 3 details the description given to the subjects for each feature, aimed at reducing the risk of semantic ambiguity.

Table 3—Description of the four subjective noise features.

Noise 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

Features	*A Stimulus*				*B Stimulus*		
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+++
	Much more than	*More than*	*Slightly more than*	*Equal to*	*Slightly more than*	*More than*	*Much more than*

Fig. 8—Response scale for each pair of sound stimuli.

Each subject was allowed to listen to each stimulus as much as needed to give the rating, choosing a value on a 7-level scale, as shown in Fig. 8. When all the features were evaluated, the test proceeded to the following pair.

The listening sequence was formed by sixteen pairs, i.e., the fifteen combinations and the repetition of the first pair heard by each subject, in order to check the consistency of his responses.

The sixteen pairs were arranged in a random sequence according to the digram balanced Latin Square design, in order to avoid any sequence effect[29]. The presentation order of the noise features was randomized among the listeners as well.

At the beginning of each listening session, the experimenter gave the subject verbal instructions on the experimental procedure and then presented a random sequence of all the six sound stimuli to acquaint the subject with the experiment.

3.2 Results of the Subjective Evaluation

In subjective tests, the consistency check of the listening jury is a basic requirement for further analysis and it can be evaluated in various ways[30,31]. In this study, the consistency check was based on two methods: the assessment of the number of circular triads in the observed judgments, and the repetition error, i.e. the difference in judgment between the first training pair and the same pair re-evaluated later on.

For the listening jury that took part in the experiment, all the ratings given by the subjects satisfied the consistency test for each feature. The smallest repetition error was obtained for the "L" and "B" features which are inherent characteristics of the noise and, therefore, easier to evaluate. On the contrary the "T" and "CL" features, depending on the noise exposure time, gave larger repetition error, even if still acceptable, because of difficulties for the subjects to give ratings "as if they had been working at the operator station of the machine for two hours continuously".

For each feature, the subjective ratings of the six stimuli were computed by pooling the marks into two categories: significant difference (marks "+++" and

Table 4—Subjective ratings of "significant difference" for the four noise features, in percentage values.

Sound Stimuli	Noise Features			
	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%**
$\mathbf{U_{-5}}$	**15.6%**	**21.1%**	**15.6%**	**26.7%**
$\mathbf{C_{-5}}$	**4.4%**	**4.4%**	**6.7%**	**1.1%**
U_{-10}	2.2%	2.2%	2.2%	13.3%

"++" added together) and no significant difference (marks "+" and "=" added together). The ratings given by the whole listening jury for the significant difference of each feature are shown in Table 4. These ratings were normalized with respect to the maximum score that each stimulus could have obtained and therefore are expressed as percentage values. In the grey area of Table 4 the subjective ratings of "significant difference" obtained for controlled and uncontrolled signals with the same A-weighted overall sound pressure level can be read. These results show that the reduction of the low frequency noise components brought on by the ANC system positively influenced the subjective evaluations with respect to all the noise features, no matter what the level of the playback. In both cases, controlled and uncontrolled signals had the same noise components at the medium-high frequencies and significant differences in the low frequency range, confirming that a reduction of the low frequency noise components is positively judged whenever comparing sounds with the same A-weighted overall level.

In order to exhibit the effect of the overall level on the perception of these sound features, in Fig. 9 the subjective ratings of the stimuli with an equal L_{eq} level

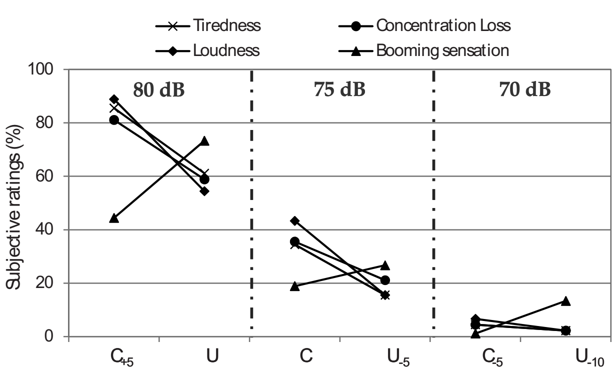

Fig. 9—Subjective ratings for stimuli with equal L_{eq} level.

have been linked to each other by a line. In such a case, a different behaviour appeared for the four noise features.

As far as the T, CL and L features are concerned, when controlled and uncontrolled stimuli with the same L_{eq} level are compared to each other, 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 mainly depend on the spectral modification due to the active noise control system and not on the overall level. In fact, stimulus U is more booming than stimulus C_{+5} even if the latter has a higher A-weighted level, thus a predominance of the energy content in the medium-high frequency.

4 CONCLUSIONS

A very simple and cheap ANC architecture was tested at the operator's station of a skid steer loader. For this purpose, a commercially-available ANC device, following a single channel adaptive feed-forward scheme, was used for tests with the further limitation that its implementation was not to require any significant modification in the standard layout of the cab in order to minimize the economic impact. The efficiency of this ANC system was evaluated in terms of sound pressure level reduction while its efficacy was subjectively verified by means of specific laboratory listening tests. In these tests, a group of expert operators of earth-moving machines had to judge the modifications caused by the ANC device with regards to some important noise features (tiredness, concentration loss, loudness and booming sensation) in order to qualify comfort and working safety conditions for the operator.

As for the decrease of the sound pressure levels, results showed that the ANC system produced a relevant noise reduction in the engine periodic noise components and also a reduction in the overall sound pressure level ranging from 5 to 10 dB. As for the A-weighted sound pressure level, the reduction was considerably lower than the others (it never exceeded 2 dB) and it turned out to be insignificant at engine speed values higher than 2000 rpm.

Subjective tests showed that 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 proved significant differences only at low frequencies, no matter what the playback level.

On the contrary, 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 subjects always judged the controlled signal worse than the uncontrolled one compared to "CL," "T" and "L" attributes, no matter what the playback level. Finally, when judging 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 middle-high frequency.

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