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SOUND QUALITY AS A TOOL TO IMPROVE THE NOISE CLIMATE AT THE OPERATOR'S STATION IN EARTH-MOVING MACHINES

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ABSTRACT
Binaural noise recordings at the operator's station of a construction machine have been taken and modified in sound levels and spectra in order to simulate the effects due to active noise control systems (ANCS) and to study how these modifications may influence the subjective ratings of some noise features. For this purpose, six sound stimuli have been used in laboratory listening tests carried out according to the paired comparison procedure, where sixteen subjects were asked to assess the stimuli in terms of tiredness, concentration loss, loud and booming. The ratings, given on a 7-value scale, show that the overall level is the predominant factor for all the features except for booming; the latter feature, instead, is more affected by the ANCS. To improve the operator's comfort and working safety, the ANCS should be applied in conjunction with a control of the noise components in the middle-high frequency range.

1 - INTRODUCTION
According to the Italian legislation, construction machinery manufacturers must fulfil strict requirements to guarantee safety conditions for the operator. In this respect, noise reduction and acoustic comfort have become factors of ever-growing importance in the machine design and great efforts are addressed to their improvement. Therefore, a deeper knowledge of the relationships between auditory perception and relevant characteristics of the noise affecting the operator's working safety is strongly needed, as it contributes to improve the efficiency of noise reduction treatments.
At present, the sound quality approach in the automotive field has proved to be a valuable method to optimize the vehicle acoustic comfort. In order to investigate the effectiveness of such an approach aimed at improving the operator working conditions in construction machineries, a research project has been undertaken and promising results have been obtained in its preliminary phase [1]. The present paper describes further laboratory experiments designed to investigate in more detail how energy modifications in the noise signals and spectral changes induced by active noise control systems affect the subjective ratings. These ratings has been given with respect to four noise features which take into account some characteristics of the sound, important for the operator's comfort and working safety conditions.

2 - SOUND STIMULI
The noise at the operator's station of a skid steer loader has been binaurally recorded by a torso-head manikin under a stationary idle condition and engine running at 2350 rpm (stimulus A). The recordings, both at left and right ear, have been modified to simulate the effect of an active noise control system driven by the engine firing frequency. For this purpose, the spectra at the two ears have been filtered by a notch filter centered at 78.5 Hz and providing a 20 dB attenuation in a frequency range of $\pm$1 Hz around the center frequency. As this attenuation lowered the overall equivalent level L_{eq} of 5 dB, an increase of the same amount has been applied to L_{eq}, providing a further stimulus (AF).
In addition, to study the effect of the L_{eq} level on the perception of some sound features, each of the two sound stimuli has been played back at three different overall L_{eq} levels, namely 80, 75 and 70 dB. None

of these levels, indeed, reproduces the actual noise at the operator's station of the machine. However, they have been selected mainly to avoid any hazardous hearing effects on the listeners and because they could better highlight the influence on the auditory perception of the noise features other than the overall energy content.
The overall linear and A-weighted equivalent sound levels of the six sound stimuli, as well as their loudness values (N), determined according to Zwicker method as in ISO 532-B:1975, are shown in Tab. I.

	Noise Codes					
Descriptors	A	A_{-5}	A_{-10}	AF	AF_{-5}	AF_{-10}
L_{eq} dB	80	75	70	80	75	70
L_{Aeq} dB(A)	73	68	63	78	73	68
N sones	35	26	19	45	33	24

Table 1: Acoustical parameters for the six sound stimuli.

3 - SUBJECTIVE LISTENING TESTS

The six sound stimuli have been presented in a quiet environment by headphones to a listening jury of sixteen subjects, tested one at a time, using the paired comparison method. Each sound stimulus had a time duration of 4 s, including a 400 ms fade in. The listening sequence was formed by sixteen pairs, arranged in a diagram-balanced Latin Square design, that is, the fifteen combinations of two stimuli chosen from a group of six and the repetition of the pair heard first by each subject, in order to check the consistency of his responses.
Four noise features relating to the operator's comfort and working safety conditions have been chosen for the subjective evaluation, that is tiredness (T), concentration loss (CL), loud (L) and booming (B). Regarding the first two features, the subject had to project his evaluation into a two hour continuous exposure.
The subject had the control of the test and could decide when to start it; then, after listening entirely each pair of sound stimuli, he could listen to the pair again as many times as he wished until he was able to give his rating. He was asked to evaluate the difference between the sounds in the pair (e.g. sounds A and AF) referring to each of the four noise features, whose presentation order was randomized among the listeners. The ratings were given choosing a value on a 7-level scale, e.g. A+++ A++ A+ A=AF AF+ AF++ AF+++. According to the above scale, for each feature, A+++ meant "stimulus A *much more than* AF", A++ "A *more than* AF", A+ "A *slightly more* than AF", A=AF stood for *no difference* between the sounds in the pair. Likewise, AF+ AF++ AF+++ had the same meaning, in the reverse order [2]. When all the features had been evaluated, the test proceeded to the following pair.
At the beginning of the listening session, the experimenter gave to the subject verbal instructions on the experimental procedure and on the meaning of the noise features under investigation. Finally, he presented a random sequence of all the six noise stimuli to acquaint the subject with the experiment.

4 - RESULTS AND DISCUSSION

All the ratings given by the subjects satisfied the consistency test and, therefore, were considered in the data analysis. For each feature, the reliability of the listener's judgements has been evaluated considering the repetition error, that is the difference between the rating given for the pair first heard and that corresponding to the same pair repeated later in the sequence. The means (absolute values) and standard deviations of these differences, over all the subjects and for each feature, are shown in Tab. II.

	Sound features			
	Tiredness (T)	Concentration loss (CL)	Loud (L)	Booming (B)
Mean value of differences	0.6	0.9	0.6	0.6
Standard Deviation	0.96	0.93	0.72	0.72

Table 2: Accuracy of the listening jury responses.

The smallest repetition error have been 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 were working at the operator's 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 "++" added together) and "*no significant difference*" (marks "+" and "=" added together). In the table of Fig. 1 are reported the percentage values of each feature ratings corresponding to *significant difference*, together with the L_{eq} and L_{Aeq} levels for all the six stimuli.
For any features, the ranking of the subjective responses depends on the overall level of the stimuli. The influence of the sound energy spectral distribution on the subjective judgements can be drawn from the plot.
The percentage scores of the stimuli with equal L_{eq} level have been connected each other by a line. As the "T", "CL" and "L" features are concerned, the AF stimuli are always rated worse than the corresponding A stimuli and this trend is observed for all the three different values of L_{eq}. Considering the spectrum shape, the above result could be interpreted in terms of predominance of the energy content in the medium-high frequency on the subjective ratings. The "B" feature shows an opposite trend, as at the same overall L_{eq} the A stimuli are rated worse than the corresponding AF stimuli. Thus, the ratings appear to be primarily dependent on the spectral modification at the engine firing frequency.
The effect on the subjective responses of a selective reduction due to the active noise control simulation becomes significant when comparing sounds with the same band levels except for that at the engine firing frequency. In such a condition (italic-bold characters in the table of Fig. 1), the filtered stimuli show subjective ratings lower than the unfiltered ones.
Finally, for each feature, the correlation between objective and subjective ratings has been determined in terms of Spearman correlation coefficients. For "T", "CL" and "L" features, loudness N shows the best correlation (r_s=1) although high values have been obtained also for L_{eq} and L_{Aeq} (0.96 and 0.97, respectively). As "B" feature is concerned, the correlation with all the acoustical parameters is slightly lower.

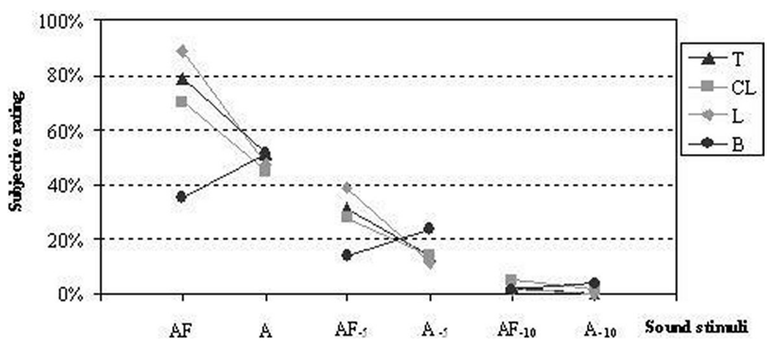

Figure 1: Subjective ratings for the four features.

			Sound features			
L_{eq}	L_{Aeq}	*Stimuli*	T	CL	L	B
70	63	A-10	0	1.3	0	3.8
	68	***AF-10***	***2.5***	***5.0***	***1.3***	***1.3***
75		***A-5***	***13.8***	***13.8***	***11.3***	***23.8***
	73	***AF-5***	***31.3***	***27.5***	***38.8***	***13.8***
80		***A***	***51.3***	***45.0***	***47.5***	***51.3***
	78	AF	78.8	70.0	88.8	35.0

Table 3: Subjective ratings for the four features.

5 - CONCLUSIONS

As expected, the study shows that either modifications of overall noise levels and changes in the noise spectra significantly affect the subjective evaluations with respect to the four noise features selected to represent the operator's comfort and working safety conditions (tiredness, concentration loss, loud and booming).

Although sound stimuli were presented at levels lower than the actual one at the operator's station, the influence of the overall level is still predominant in determining the subjective ranking for all the four features. The effect on the subjective responses of a selective reduction, due to the active noise control simulation, becomes significant when comparing sounds with the same band levels except for that at the engine firing frequency. 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 is associated with a level control in the medium-high frequency range.

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