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A Perception-Based Method for the Noise Control of Construction Machines

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During operation, construction machines generate high noise levels which can adversely affect the health and the job performance of operators. The noise control techniques currently applied to reduce the noise transmitted into the operator cab are all based on the decrease of the sound pressure level. Merely reducing this noise parameter may be suitable for the compliance with the legislative requirements but, unfortunately, it is not sufficient to improve the subjective human response to noise. The absolute necessity to guarantee comfortable and safe conditions for workers, requires a change of perspective and the identification of *different* noise control criteria able to combine the reduction of noise levels with that of psychophysical descriptors representing those noise attributes related to the subjective acoustical discomfort.

This paper presents the results of a study concerning the "customization" of a methodology based on Sound Quality for the noise control of construction machines. The purpose is to define new hearing-related criteria for the noise control able to guarantee not only reduced noise levels at the operator position but also a reduced annoyance perception.

Keywords: noise control, acoustic design, sound quality, annoyance, psychoacoustics, construction machines.

1. Introduction

The noise generated by construction machines is very high; it has a negative impact on people in the surrounding areas and, even more, on the machine operators. At present, the sound power levels generated by these machines range from 93 to 116 dBA, depending on the engine net installed power. On the other hand, noise levels at the operator position are generally in the range 78–85 dBA, even if levels higher than 85 dBA are not uncommon. Many studies have shown that long exposures to moderate or high levels of noise can cause permanent damage to the hearing mechanisms of the inner ear, resulting in an increase of the hearing threshold level at certain frequencies. Prolonged exposure to high noise levels can have other physiological and psychological effects, including hypertension, heart trouble, fatigue, reduced motor efficiency and annoyance. All these effects greatly increase the possibility for operators to make mistakes during their job. In addition, the noise at the operator station can also have masking effects on other acoustical signals which could be very important for the worker in order to properly operate. For all the above reasons the noise control at the operator station is a key issue for these machines.

The noise control methodologies currently applied to make construction machines quieter and comfortable have been addressed to identify the main noise sources and the related noise transmission paths. As a result, nowadays the generated sound power levels and the sound pressure levels at the operator position generally meet the current legislative requirements. Despite this compliance, however, the noise condition at the operator station is still unsafe.

This paper summarises the main results of a study aimed at overcoming the above limitation. A methodology based on Sound Quality was developed in order to identify new hearing-related criteria for the noise control able to guarantee not only reduced noise levels but also reduced annoyance conditions.

2. Noise control at the operator position: the current situation

Nowadays, the noise control of construction machines is usually considered only when these machines are already in production rather than at their design stage. In particular, the noise reduction at the operator station is obtained by passive noise control strategies, based on the application of more than one methodology to ensure great confidence in the identification of the major noise sources and the relevant transmission paths.

Sound intensity technique is often used for this purpose. Figure 1 shows some results of a study performed by the author with the purpose to reduce the noise level inside the cab of a loader already in production (Carletti, 2006).

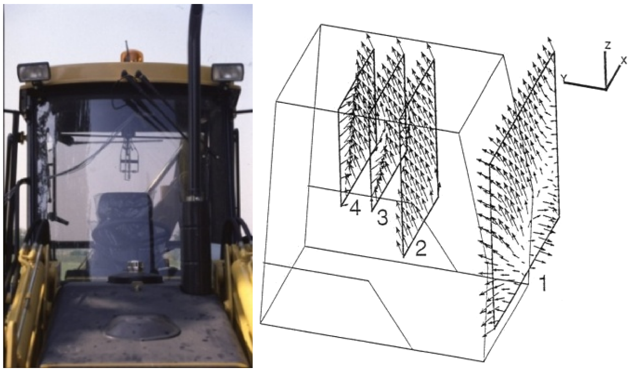

Fig. 1. Sound intensity tests on grids of points inside and outside the cab of a loader.

The vector sound intensity method was successfully used to map the sound path from the engine power group to the operator cab. Tests were performed on grids of points inside and outside the cab while the machine was operating in stationary conditions. The overall sound intensity maps in this figure give a visual representation of the sound energy flux from the engine compartment. They clearly show that the noise enters into the cab mainly from the rear window (window seals were not effective) and the floor, especially in the areas around the levers.

Also the order tracking technique is often applied to these machines in order to identify the major noise sources and their relative contributions to the overall noise inside the cab. Its suitability is due to the fact that in these machines all the noise components from the main noise sources (engine cooling system, hydraulic system) are strictly related to the engine rotational speed value (Willemsena *et al.*, 2009).

Besides the several studies concerning noise control strategies on machines already in production, methodologies and tools integrating vibroacoustic modelling and experimental analyses are nowadays widely applied in order to simulate the dynamic behaviour of different machine components, such as hydraulic pumps, cooling system fans and air conveyors, exhaust mufflers (Kim *et al.*, 2007; Mucchi, 2007). The purpose of vibroacoustic modelling is to predict the effects of each design modification on the emitted noise as well as to reduce the number of experiments required for developing the prototype. Figure 2 shows some results of a study aimed at developing a vibroacoustic model

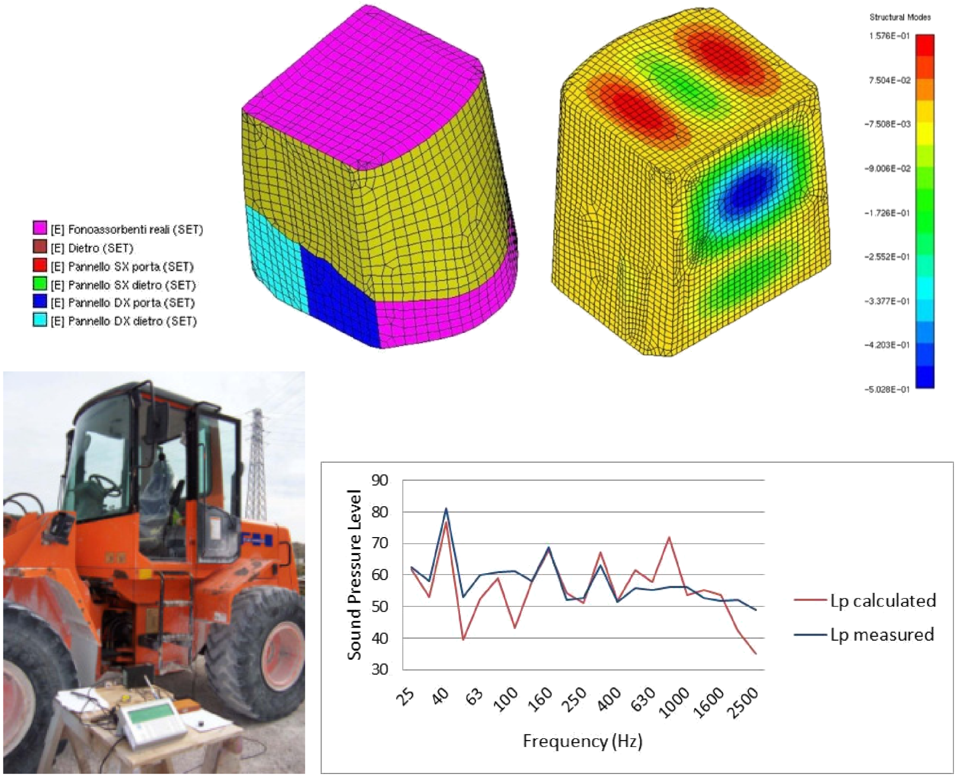

Fig. 2. Vibroacoustic model of a loader cab: comparison between numerical and experimental sound pressure levels at the operator position (left ear).

of a loader cab for the simulation of the acoustic inner field and the prediction of the influence of the different design options on its dynamic behaviour (Bregant *et al.*, 2006).

The active noise control (ANC) approach seems particularly suitable to reduce the noise at the operator position of these machines, as the dominant noise components are all included in the middle-low frequency range and the volume to be controlled is rather limited. However, only a limited bibliography exists dealing with the use of this technique inside the machine cabs and most of the available papers describe only the simulation of the ANC process.

A study was undertaken by the author on the application of an ANC device to reduce the noise level at the operator station of a skid steer loader, with the constrain that the implemented scheme had to avoid any significant modification in the standard layout of the cabin, in order to minimize the economic impact (Carletti, Pedrielli, 2009).

A commercially-available ANC device, following a single channel adaptive feed-forward scheme, was then used for tests. Figure 3 shows the machine object of this study and the layout of the active noise control system used for experiments.

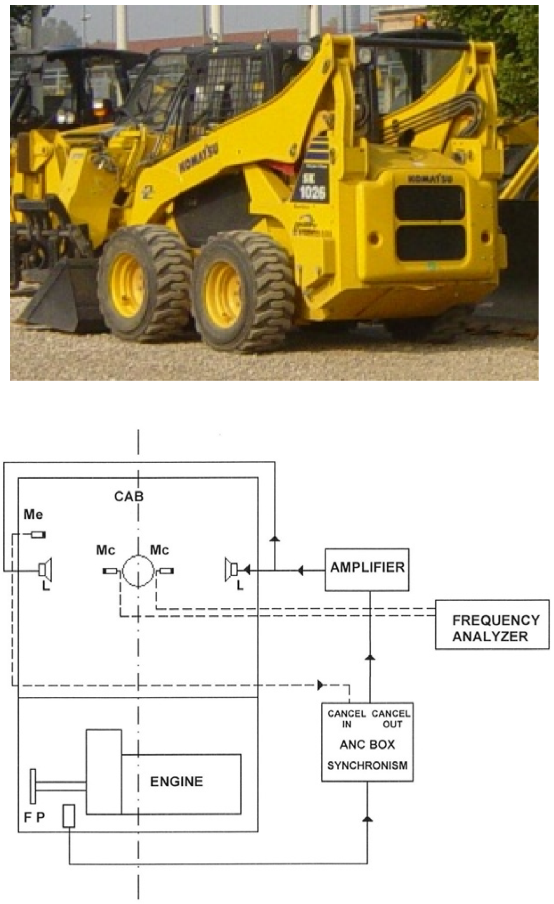

Fig. 3. Skid steer loaders and layout of the active noise control system. L – loudspeakers, Me – error microphone, Mc – monitoring microphones, FP – photoelectric probe.

Results confirmed the capability of such a cheap ANC system to significantly reduce the dominant engine periodic noise components and the overall sound pressure level within the space where the operator's head is located during his/her work. On the contrary, its efficiency in reducing the A-weighted sound pressure level turned out to be quite limited.

3. Noise control at the operator position: new perspectives

All the above examples show that the reduction of the energy-oriented noise parameters is the main target nowadays driving the noise control of construction machines. Noise control solutions have to lead to lower A-weighted sound power levels (noise emission in environment) and lower A-weighted sound pressure levels (operator ear position) in order to comply with the current regulations. Unfortunately, the reduction of these parameters has proved to be the right solution for the above purpose but absolutely ineffective to guarantee an improvement of the subjective human response to noise, especially for sounds exceeding 60 dB, which is a common condition inside these machine cabs (Genuit, 1999).

Consequently, a different noise control perspective turns out to be necessary to overcome this limitation. With this purpose, an approach based on Sound Quality (SQ) was developed in order to improve the noise conditions at the operator station of loaders. Figure 4 shows the layout of the developed procedure.

The starting point of this SQ-based approach was the establishment of the target. Taking into account the peculiarity of this "working environment" (machine cab), the noise control target included two main *expectations*. On the one hand, the simultaneous reduction of noise levels and perceived annoyance. On the other hand, the guarantee that the reduced noise signal maintained its original inherent function of carrier of information about the state of operation of the machine.

The next key point was the collection of a significant amount of noise signals at the working station of different loaders, all recorded in the same way as they would be heard by an operator in the same position. These recordings had to be representative of the noise at the operator ear position for all the possible operating conditions. For this purpose, a huge amount of binaural recordings were taken at the operator station of many different loaders in stationary and dynamic conditions. The recordings were performed while the machine was repeating the same typical work cycle, with the use of two different usual materials (gravel and loam) and in stationary conditions, with the engine running at a fixed speed. Figure 5 shows the different setup used for binaural measurements, both in stationary and dynamic conditions.

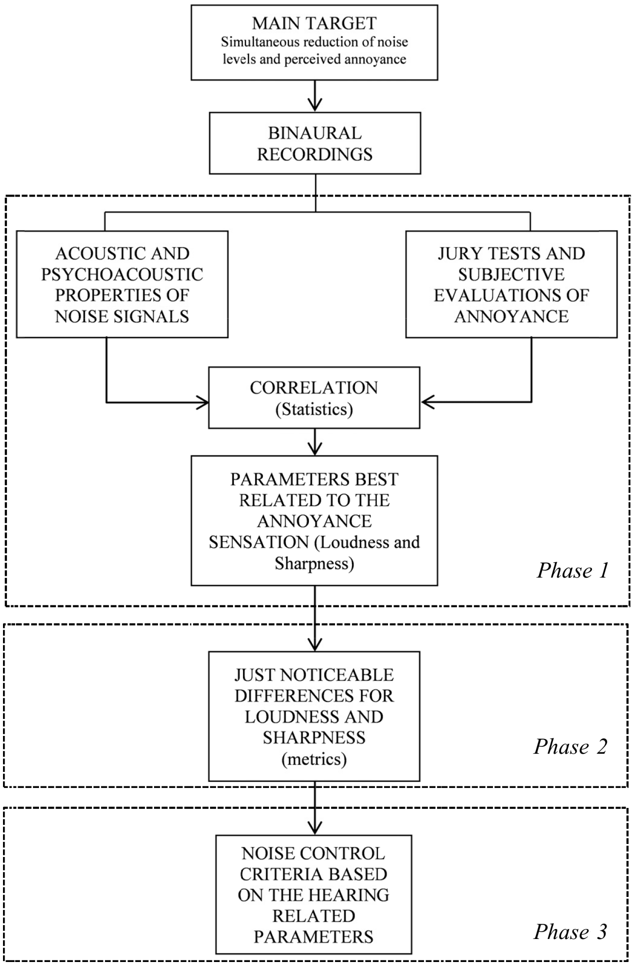

Fig. 4. Development process of the SQ approach applied to loaders.

This hearing-related methodology includes three main phases (see diagram in Fig. 4).

Phase 1 was aimed at obtaining a deeper knowledge of the relationship between the multidimensional characteristics of the noise signals at the operator position (frequency content, time structure, modulations, ...) and the relevant auditory perception of annoyance. The target was the identification of hearing-related parameters mainly affecting the auditory perception of annoyance. This purpose required the following two main tasks.

a. Listening tests, based on the paired-comparison procedure. These tests were performed in laboratory, under stable, controlled boundary conditions (in order to guarantee a high reproducibility of the test results) and involved many juries of subjects. The main objective of these investigations was the assessment of a subjective scale of annoyance values for the several noise recorded signals. A ranking of subjective judgements of annoyance related to all the different machines and operating conditions was so established.

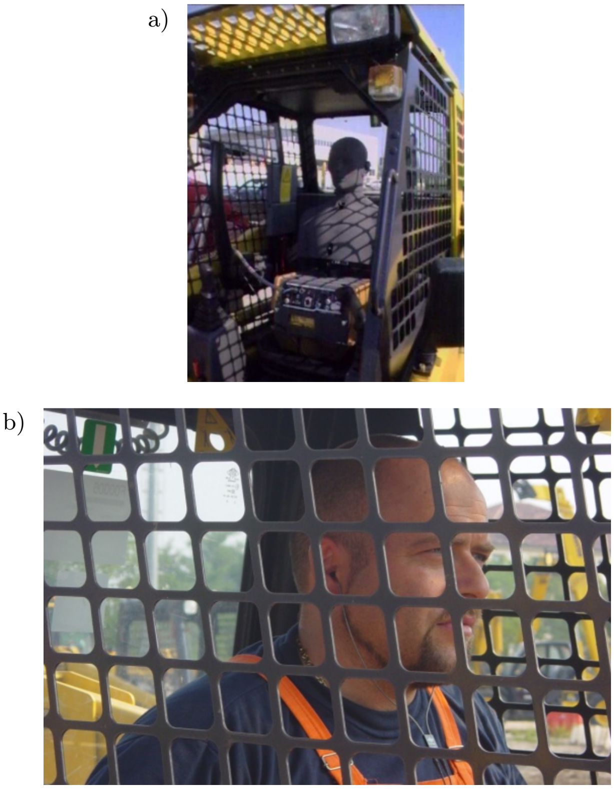

Fig. 5. Binaural recording setup: a) stationary conditions, b) dynamic conditions.

b. Noise signal objective analyses. Based on the results of a previous 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 Leq and LAeq (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.

On the basis of the Pearson correlation coefficients obtained between the subjective annoyance ratings and the objective parameters, the hearing-related parameters mainly affecting the auditory perception of annoyance were finally identified. Loudness and sharpness are the objective parameters better describing the auditory perception of annoyance at the operator station of loaders. Moreover, in the case of time-varying noise signals, the value of the fifth percentile of sharpness (S_5) turns out to be the parameter better describing the effects of time-variability on annoyance.

Phase 2 was aimed at developing a specific metrics for loudness and sharpness. The knowledge of the parameters best correlated to the annoyance sensation, indeed, is insufficient to develop a methodology able to identify the basic criteria for noise control. Tiny variations in stimulus magnitude may not lead to a variation in sensation magnitude. Then, it was necessary to determine the minimum variation in these parameters which led to a variation in the sensation (*Just Noticeable Differences* (JNDs)) (Pedrielli, Carletti, 2008). For this investigation a binaural noise signal recorded at the operator station of the loader in stationary conditions was used as reference signal. This signal was post-processed to create two sets of sound stimuli with different loudness or sharpness values, respectively. Subjective listening tests were performed following the classical Method of Limits in order to detect the step size of each psychoacoustic parameter that leads to a difference in the hearing sensation. In the experiments, a total number of six runs (three ascending alternated to three descending runs) were planned for each loudness and sharpness subjective test. Three test sessions, different from each other as far as the sound pressure levels of the reference stimulus were undertaken (65 dB, 73 dB, 82 dB). The step size of these parameters that leads to a difference in the hearing sensation of a group of people was described following a statistical approach. Cumulative distributions rather than unique values of just noticeable differences, indeed, make it possible to choose the just noticeable difference value depending on the specific target. Figure 6 shows the loudness and sharpness cumulative distributions for the three loudness/sharpness tests, having the reference stimulus with different sound pressure levels. The 75° percentile was considered appropriate to guarantee that the improvement of the operator comfort conditions was extensively appreciated. For loaders, where the sound pressure levels at the operator position is around 82 dB, the cumulative distribution for a similar presentation level must be considered. Therefore, the just noticeable difference in loudness and sharpness resulting from the test with the highest sound pressure level of the reference stimulus, were assessed as 0.8 sone and 0.04 acum, respectively.

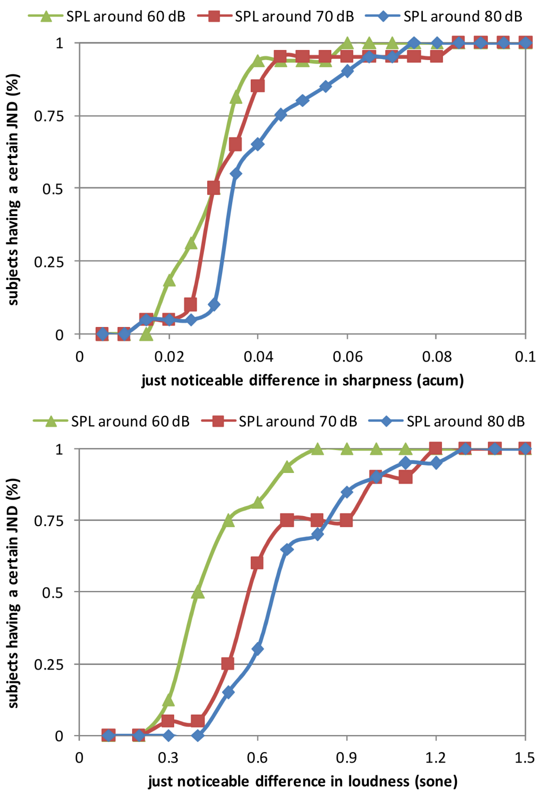

Fig. 6. Loudness and sharpness cumulative distributions for the three loudness/sharpness tests.

Phase 3, still in progress, is aimed at the exploitation of the above results in new criteria for the noise control based on the identified parameters which are well related to the annoyance sensation.

In this respect, a preliminary investigation was undertaken in order to verify whether the simultaneous reduction of loudness and sharpness could be a promising target for the noise control of these machines. A numerical optimisation procedure, based on a multi-objective genetic algorithm, was applied to some noise signals recorded at the operator station in stationary condition in order to analytically identify the noise spectrum modifications which led to the simultaneous reduction of these parameters (Carletti, Pedrielli, 2010). Then the same procedure was "adapted" to be suitable for time-varying noise signals, typical of real working conditions. New input variables describing the time variant characteristics of the system were identified and a numerical module for the correct calculation of loudness for time-variant sounds was developed according to the DIN-45631/A1 procedure. In this case the target was the simultaneous minimisation of the loudness and sharpness percentile values N_{50} and S_5 (Carletti, Pedrielli, 2011).

Very interesting results were obtained. Among the several solutions of the numerical process, some of the optimized noise spectra showed important reductions of the noise contributions due to the hydraulic system, confirming the relevance of this source in producing bad noise conditions. On the other hand, listening tests using optimized and original noise signals confirmed the subjective relevance of the simultaneous reduction of loudness and sharpness in reducing the annoyance sensation.

4. Conclusions

Sound quality targets were developed for the noise control of loaders in order to really combine the requirement of reduced noise levels with that of safe and comfortable conditions for the operators of these machines. A hearing-related approach was developed in order to relate the physical characteristics of the noise signals in typical working conditions with other noise features affecting the auditory perception of annoyance. A ranking of subjective judgements of annoyance related to the different binaural noise signals was assessed by performing jury tests. In parallel, the most relevant acoustic and psychoacoustic parameters characterising these signals were calculated. On the basis of the Pearson correlation coefficients obtained between the subjective ratings and the computed metrics, the hearing-related parameters mainly affecting the auditory perception of annoyance were finally identified (loudness and sharpness). The detection of the minimum difference in these parameters which leads to a difference in the hearing sensation were then obtained by subjective listening tests following the Method of Limits. The availability of these new hearing-related parameters and the knowledge of their relevant JNDs could really open new possibilities to the noise control of these machines, towards effective and efficient vibro-acoustic solutions able to guarantee safe conditions and comfort.

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