

Digital high-speed sampling of combined exposure to noise and vibration

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PEKKARINEN J, STARCK J. Digital high-speed sampling of combined exposure to noise and vibration. *Scand J Work Environ Health* 12 (1986) 327–331. The digital high-speed sampling technique was applied to simultaneous measurements of exposure to noise and vibration among workers who used hand-held power tools in a shipyard. The transducers were two accelerometers and two microphones which measured the transmission of vibration acceleration from the handle of the tool to the wrist and the attenuation of noise by the earmuffs. The measurements were taken by a microcomputer-controlled digital multichannel sampling unit. An analogue-digital converter was used with a 100-kHz scanner for multichannel signal acquisition in the 10 kHz bandwidth. The sound pressure was A-weighted, and the vibration acceleration was both unweighted and weighted according to the guidelines of the International Organization for Standardization. Impulsiveness was determined as the difference between the peak and root-mean-square levels. The noise exposure was 81 dB during grinding and 85 dB during hammering. The earmuffs provided protection against impulse noise at least when the impulses contained high frequencies. The transmission loss of vibration acceleration between the tool handle and wrist was 45 dB for grinding and 29 dB for hammering. The transmission of noise and vibration was affected by the frequency content and impulsiveness of the signals.

Key terms: attenuation, combined effects, crest factor, earmuffs, hearing threshold, impulsiveness, microcomputer measurements, signal analysis, vibration-induced white finger.

Workers' exposure to local vibration is usually accompanied by exposure to noise. Combined exposure to noise and vibration has been shown to increase the permanent (PTS) or temporary (TTS) threshold shift (6, 15, 16). This effect has been confirmed also in laboratory experiments (11).

In addition to the energy content of noise (7, 8) and vibration (9), impulsiveness may also be a risk factor associated with the permanent threshold shift (3, 12) and vibration-induced white finger (VWF) (18, 20, 22). Also in animal studies impulse noise has generated higher permanent and temporary threshold shifts than continuous noise with the same energy (12). The risk estimation models developed for continuous noise may not be adequate for impulse noise (5, 21).

In the present study a digital high-speed sampling technique was applied that allowed accurate amplitude determination, simultaneous multichannel measurements, and application of waveform analysis methods and statistics. Impulsiveness was determined according to the definition based on the difference between the peak and root-mean-square (rms) levels of the signal (12, 19).

This paper describes measurements taken in a shipyard to investigate the attenuation of noise by earmuffs and the transmission of vibration from the tool to the wrist.

Digital measurement method

Computer characteristics

The measurements were taken by a digital multichannel sampling unit (Hewlett-Packard 6944) controlled with a microcomputer (Hewlett-Packard 9920) (figure 1). The noise and vibration were sampled with an analogue-digital converter connected to a 16-channel scanner. The maximum sampling rate was 100 000 samples/s. The channels could also be scanned 100 000 times/s. The resolution was 12 bits, corresponding to 72 dB.

The software included Pascal subroutines for fast data acquisition, parameter selection during sampling, and computing subroutines. These subroutines were linked to the main program (Basic), which contained graphics, statistical programs, and waveform analysis.

Noise and vibration measurements

Noise was measured outside and inside the earmuff simultaneously. Inside the earmuff a miniature microphone (Knowles 1785 LY072) was attached to the earlobe at the middle of the ear canal. Outside the earmuff a microphone of the same type was attached to the headband. Both signals were A-weighted in the preamplifiers.

Accelerometers were attached both to the handle of the tool [Brüel & Kjaer (B & K) 4375] with a mechanical filter (B & K, UA 0559) and to the operator's wrist (B & K 4371) (4, 9). The direction of the accelerometer on the handle was parallel to that on the wrist.

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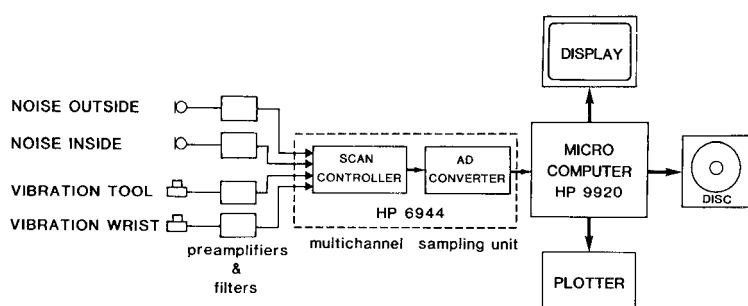


Figure 1. The microcomputer system used for the noise and vibration measurements.

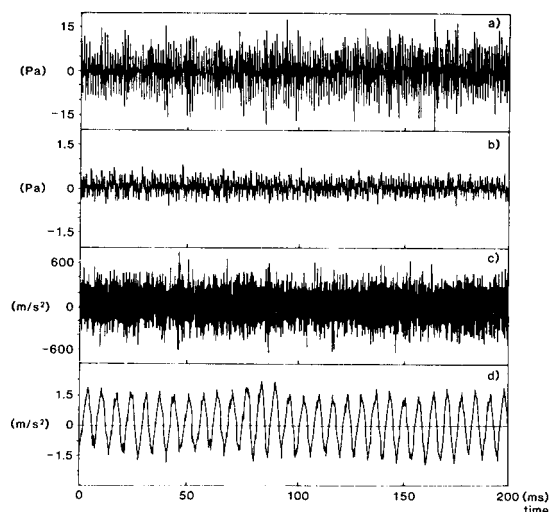


Figure 2. The sampled blocks [A-weighted sound pressure outside the earmuffs (a), A-weighted sound pressure inside the earmuffs (b), unweighted vibration acceleration on the handle of the tool (c), and unweighted vibration acceleration on the wrist of the worker (d)] in the time domain from the pneumatic grinding.

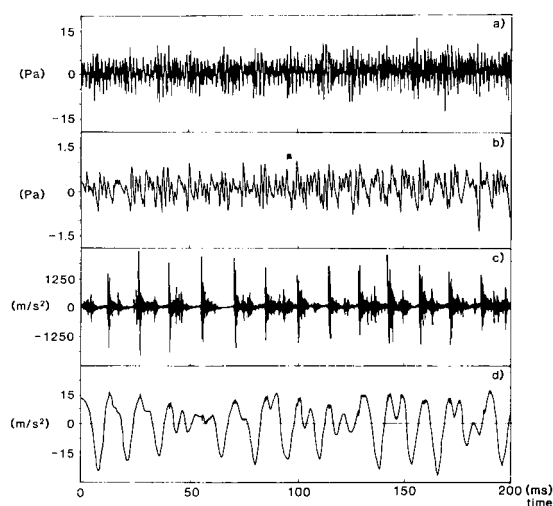


Figure 3. The sampled blocks [A-weighted sound pressure outside the earmuffs (a), A-weighted sound pressure inside the earmuffs (b), unweighted vibration acceleration on the handle of the tool (c), and unweighted vibration acceleration on the wrist of the worker (d)] in the time domain from the pneumatic hammering.

Table 1. Peak levels, root-mean-square (rms) levels, and impulsiveness of noise outside and inside the earmuffs and the vibration on the handle of the tool and the wrist, as well as the attenuation of noise by the earmuffs and the transmission loss of the vibration between the handle of the tool and the wrist of the operator. A pneumatic metal grinder (Yakata) and pneumatic hammer (Atlas Copco) were measured during work in a shipyard. (rms = root-mean-square)

	Grinding			Hammering		
	Peak (dB)	rms (dB)	Impulsiveness (dB)	Peak (dB)	rms (dB)	Impulsiveness (dB)
Noise						
Outside the earmuffs	119	108	11	116	104	12
Inside the earmuffs	92	81	11	93	85	8
Attenuation by the earmuffs	27	27	0	23	19	4
Vibration						
Tool	177	165	12	187	169	18
Wrist	126	120	6	144	140	4
Transmission loss	51	45	6	43	29	14

The signals from the accelerometers were sampled unweighted and weighted (9). The preamplifiers and analogue filters (Wärtsilä Oy, custom-made and B & K 2634) were carried on the back of the worker in a harness (total weight 3 kg). The amplified signals were connected via a 35-m cable to the multichannel

sampling unit. The computer system was adequately protected by a custom-made hermetic box against electric disturbances, heat, and dust.

The noise and vibration channels were sampled simultaneously in pairs for the analysis of the attenuation of noise by the earmuff and the transmission of

vibration. The sample rate was selected to be 40 000 Hz/channel, which was in relation to the upper frequency limit of 10 000 Hz in the preamplifiers.

With continuous sampling and averaging there were no time limitations for the sampling. A sampling time of about 10 min was found to cover several work-phases.

The peak level (L_{peak}) and the rms level (L_{rms}) were calculated from the sampled voltage values for each channel separately according to the following formulas:

$$L_{\text{peak}} = 20 \cdot \log \frac{y_{\text{max}}}{y_o}$$

and

$$L_{\text{rms}} = 20 \cdot \log \sqrt{\frac{1}{N} \sum_{i=1}^N \frac{y^2}{y_o^2}},$$

where N = number of digital samples in a block, y_{max} = the maximum amplitude in a block, y = instantaneous amplitude in a block, and y_o = reference amplitude ($p_o = 20 \cdot 10^{-6}$ Pa, $a_o = 1 \cdot 10^{-6}$ m/s²).

Impulsiveness (I) was determined according to $I = L_{\text{peak}} - L_{\text{rms}}$, and it corresponded to the crest factor of the signal (3, 12).

Frequency analysis

Signal analysis was used to explain the exposures caused by the transmission of acoustic energy. Each block containing 8 000 samples in the time domain was split into seven segments. There was an overlapping of 50 %; thus each segment contained 2 000 samples. The segmentation was used in the ensemble averaging in order to obtain a statistically consistent periodogram spectrum (2, 10, 13). These segments were windowed with a Hanning window to reduce the spectral leakage associated with finite observation intervals.

The spectra were calculated up to 10 kHz. The vibration on the wrist contained spectral energy mainly below 2 kHz, and it was thus represented also in that frequency range.

Worksites and tools measured

The measurements were taken in a shipyard assembly hall in which grinders, welders, and platers were exposed to noise and vibration generated by pneumatic grinding and pneumatic hammering. The pneumatic grinder (Yakata) had a maximum speed of 13 200 r/min; the diameter of the grinding wheel was 10 cm. The welded units were cleaned by an Atlas Copco RRC 12 pneumatic hammer. The worker wore his own Silenta Pop helmet earmuffs during the measurements.

Results

Time functions and impulsiveness

The time functions contained 8 000 samples (figures 2 and 3), which were used in the calculation of the peak

and rms values with the computer program (table 1).

Outside the earmuffs the rms levels of the noise were 4 dB higher for grinding than for hammering. The situation was reversed inside the earmuffs (table 1). The hammering impulses were only fairly visible outside the earmuffs (figure 3a). The frequency content was shifted towards low frequencies inside the earmuffs during the hammering (figure 3b).

The acceleration of vibration during the hammering was impulsive compared to that during grinding. The approximate form of the vibration signal on the wrist was triangular during grinding and sinusoidal during hammering. The transmission loss of vibration acceleration was greater for grinding than for hammering (table 1).

Frequency analysis

The grinding noise contained a pure tone of about 1 000 Hz, which could also be determined inside the earmuffs (figures 4a and 4b). The vibration spectrum had a rising slope up to 5 kHz caused by the high frequencies given off by the grinding wheel (figure 5c). Its maximum speed corresponded to a frequency of 220 Hz. The vibration acceleration measured from the wrist mainly contained frequencies below 2 kHz. The triangular shape in the time domain was composed of pure tones at the frequencies of 160, 740, and 1 480 Hz (figure 6a).

During hammering the earmuffs also effectively filtered high-frequency noise (figures 5a and 5b). The handle of the tool had a very broad spectrum (figure 5c), and the dominant frequency on the wrist was 70 Hz (figure 6b).

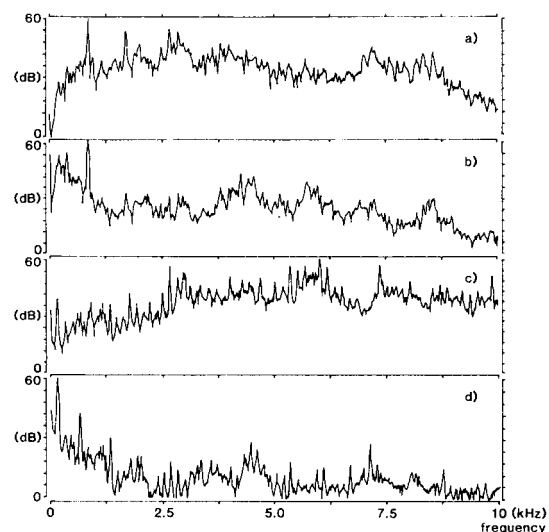


Figure 4. The periodogram spectra calculated from the time domain blocks [A-weighted sound pressure outside the earmuffs (a), A-weighted sound pressure inside the earmuffs (b), unweighted vibration acceleration on the handle of the tool (c), and unweighted vibration acceleration on the wrist of the worker (d)] of the pneumatic grinding. (See figure 2.) The vertical axis of the spectra is relative.

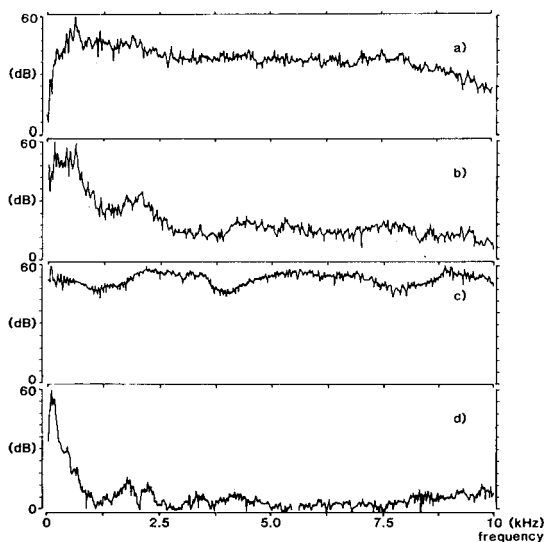


Figure 5. The periodogram spectra calculated from the time domain blocks [A-weighted sound pressure outside the earmuffs (a), A-weighted sound pressure inside the earmuffs (b), unweighted vibration acceleration on the handle of the tool (c), and unweighted vibration acceleration on the wrist of the worker (d)] of the pneumatic hammering. (See figure 3.) The vertical axis of the spectra is relative.

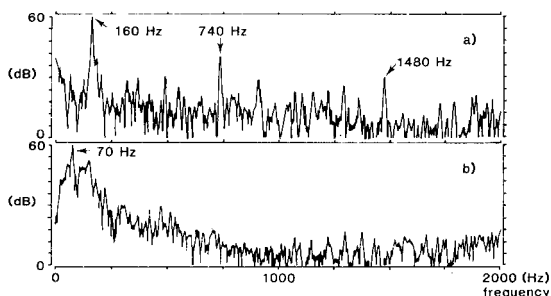


Figure 6. The periodogram spectra of unweighted vibration acceleration in the 2 kHz bandwidth on the wrist of the operator during pneumatic grinding (a) and pneumatic hammering (b). The vertical axis of the spectra is relative.

Hygienic assessment of the noise and vibration

The A-weighted rms levels inside the earmuffs were 85 dB during the hammering and 81 dB during the grinding. The former is also the occupational safety limit set for hearing conservation purposes (7).

The weighted vibration measured from the handle of the tool can be compared to the respective threshold limit values (1). The frequency-weighted values were also compared to the unweighted values measured from the wrist. During grinding the weighted value for the tool was 122 dB (1.3 m/s^2), the unweighted value for the wrist was 120 dB (1.1 m/s^2). The threshold limit values allow over 8 h of daily grinding at these levels. The corresponding values during hammering were 143 dB (13.4 m/s^2) and 140 dB (10.2 m/s^2), ac-

cording to which worktime should be limited to less than 1 h/d.

Discussion

The microcomputer connected to the multichannel sampling unit was found to have the speed, accuracy, and memory capacity needed to measure high-impulse noise and vibration levels in industrial environments. The data can be analyzed and displayed with great accuracy after the sampling. New analysis methods can later be utilized with the same exposure data.

Grinding generated higher rms noise levels outside the earmuffs than hammering, but inside the earmuffs the order was reversed. The results suggest that measurement of the ambient noise level is not sufficient to determine workers' exposure to noise when earmuffs are used. Hammering may present the risk of hearing loss if the earmuffs are in poor condition or are not a good fit.

The earmuffs seemed to protect against impulse noise at least when the impulses had a high-frequency content, as is common for industrial impulse noise. Low-frequency impulses can be expected in heavy metal industries, in wood industries, and during explosions (14).

The impulsiveness of a sinusoidal signal is 3 dB and that of a triangular signal 4.7 dB. The impulsiveness of vibration acceleration measured from the wrist was 4 dB for hammering and 6 dB for grinding. However, in practice the signal also contains random noise, which increases the impulsiveness. However, the measured sinusoidal and triangular signals were not entirely pure signals. Comparison of the data of table 1 and figures 2 and 3 shows that the calculation of impulsiveness quantifies the signals according to signal form. The signal level does not affect impulsiveness.

The acceleration of vibration during grinding generated high frequencies when compared with that during hammering. The transmission of vibration from the tool to the wrist was related to the spectrum of vibration. The rms levels of vibration acceleration were decreased by 45 dB during grinding and 29 dB during hammering. In these measurements the filter characteristics of the wrist resulted in rms levels 2–3 dB lower than those for standardized frequency weighting.

The rms acceleration measured in the frequency range of 6.3–1000 Hz has been shown to be about the same for a similar pneumatic hammer, as measured in this study, but clearly less in vertical grinding (17). The result would suggest that in grinding the vibration energy was mainly distributed to the frequencies above 1 kHz.

Conclusions

The digital sampling equipment had enough capacity and accuracy to collect simultaneously data about exposure to noise and vibration during work.

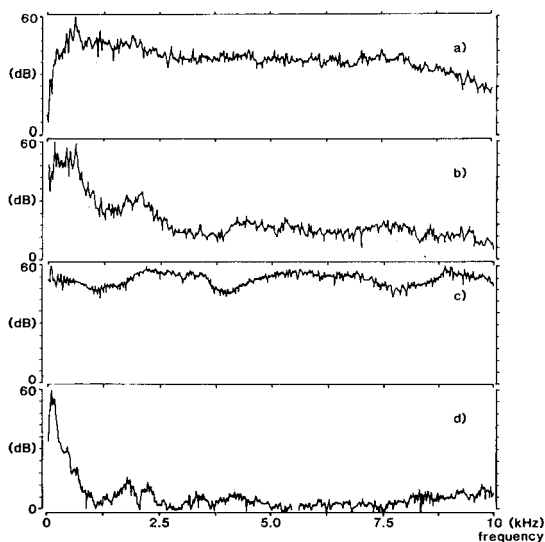


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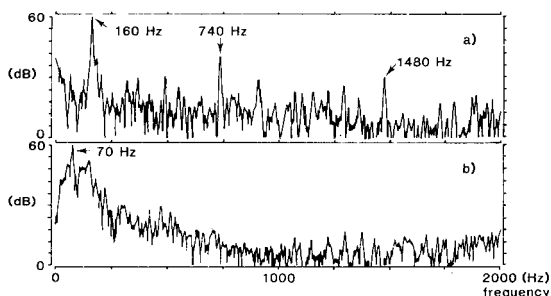


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Conclusions

The digital sampling equipment had enough capacity and accuracy to collect simultaneously data about exposure to noise and vibration during work.

Exposure to noise can be measured reliably only with a microphone inside the earmuff. The earmuffs attenuated impulsiveness so that the noise was not impulsive inside the earmuffs.

The vibration from pneumatic hammering was shown to be highly impulsive. The vibration from grinding was not impulsive. The unweighted vibration on the wrist was 2–3 dB lower than the frequency-weighted vibration on the handle of the tool.

The combined effects caused by a tool should be taken into account in tool construction. The reduction of rms vibration levels usually decreases the noise levels. Signal characteristics play an important role, however, in the transmission of acoustic energy and in the effects of combined exposure to noise and vibration.

Acknowledgments

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References

1. American Conference of Governmental Industrial Hygienists. Threshold limit values for chemical substances and physical agents in the work environment and biological exposure indices with intended changes for 1984–85. Cincinnati, OH 1984.
2. Bendat JS, Piersol AG. Engineering applications of correlation and spectral analysis. John Wiley & Sons, New York, NY 1980.
3. Brüel PV. Noise do we measure it correctly? Brüel & Kjaer A/S, Naerum 1975.
4. Färkkilä M, Starck J, Hyvärinen J, Kurppa K. Vaso-spastic symptoms caused by asymmetrical vibration exposure of the upper extremities to a pneumatic hammer. *Scand J Work Environ Health* 4 (1978) 330–335.
5. Hamernik RP, Hendersson D, Salvi R, ed. New perspectives on noise-induced hearing loss. Raven Press, New York, NY 1982.
6. Iki M, Kurumatani N, Hirata K, Moriyama T. An association between Raynaud's phenomenon and hearing loss in forestry workers. *Am Ind Hyg Assoc J* 46 (1985) 509–517.
7. International Organization for Standardization. Acoustics — Assessment of occupational noise exposure for hearing conservation purposes. Geneva 1975. (ISO 1999).
8. International Organization for Standardization. Acoustics — Assessment of occupational noise exposure for hearing conservation purposes. Geneva 1985. (ISO/DIS 1999.2).
9. International Organization for Standardization. Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration. Geneva 1984. (ISO/DIS 5349.2 — 1984).
10. Kay SM, Marple SL. Spectrum analysis — A modern perspective. *Proc IEEE* 69 (1981) 1380–1419.
11. Manninen O, ed. Combined effects of environmental factors, Tampere 22–24 Sept 1984, Finland. The International Society of Complex Environmental Studies, Tampere 1985.
12. Nilsson P, Arlinger S, ed. Proceedings of the international symposium on effects of impulse noise on hearing, August 25–27, 1980, Malmö, Sweden. *Scand Audiol* (1980): suppl 12, 348 p.
13. Papoulis A. Signal analysis. McGraw-Hill, New York, NY 1979.
14. Pekkarinen J, Starck J. Impulssimelu — Esiintymisen teollisuudessa ja vaimentuminen kupusuojaamisissa [Impulse noise — Survey in industry and the protection efficiency of earmuffs]. *Työterveyslaitoksen tutkimuksia* 2 (1984) 324–327. (English summary).
15. Pinter I. Hearing loss of forest workers and of tractor operators. In: Environmental Protection Agency, Office of Noise Abatement and Control. Proceedings of the international congress a noise as a public health problem, Dubrovnik, May 13–18, 1973. Washington, DC 1973, pp 315–327. (Report no EPA-550/9-73-008).
16. Pyykkö I, Starck J. Vibration syndrome in the etiology of occupational hearing loss. *Acta Oto Laryngol Suppl* 386 (1982) 296–300.
17. Reynolds DD, Wasserman DE, Basel R, Taylor W, Doyle TE, Asbury W. Vibration acceleration measured on pneumatic tools used in chipping and grinding operations. In: Brammer AJ, Taylor W, ed. Vibration effects on the hand and arm in industry. John Wiley & Sons, New York, NY 1982, pp 225–238.
18. Starck J, Färkkilä M, Aatola S, Pyykkö I, Korhonen O. Vibration syndrome and vibration in pedestal grinding. *Br J Ind Med* 40 (1983) 426–433.
19. Starck J. Characteristics of vibration, hand grip force, and hearing loss in vibration syndrome. University of Kuopio, Kuopio (Finland) 1984. (Original reports 4/1984, natural sciences).
20. Starck J. High impulse acceleration levels in hand-held vibratory tools: An additional factor in hazards associated with the hand-arm vibration syndrome. *Scand J Work Environ Health* 10 (1984) 171–178.
21. Sulkowski WJ. Hearing impairment caused by impulse noise: Survey in the drop forging industry. *Scand Audiol* (1980): suppl 12, 307–317.
22. Taylor W, Pearson J, Kell RL, Keighly GD. Vibration syndrome in forestry commission chain saw operators. *Br J Ind Med* 28 (1971) 83–89.