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Uncertainty in the evaluation of occupational exposure to whole-body vibration

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Abstract

Uncertainties associated with field assessments of daily exposure to whole-body vibration (WBV) have been investigated in four categories of work vehicles (fork lift trucks, wheel loaders, garbage trucks, buses) in different working conditions. A total of 50 vehicles were included in the study. WBV exposures were measured in different field conditions in marble quarries, marble laboratories, dockyards, paper mills, transportation and public utilities: over 700 individual vibration measurements were analysed to quantify relevant uncertainty components due to changes in the operators' working methods, variations in the characteristics and conditions of the machines, changes in the characteristics of the travelling surface, uncertainty in the evaluation of exposure duration, and systematic errors due to measurement equipment. The methods used in the study to calculate measurement uncertainties are in accordance with the ISO publication "Guide to the Expression of Uncertainty in Measurement". The study made it possible to isolate major sources of uncertainty in field assessment of daily exposures to WBV. The investigation revealed that, in all the field conditions, differences in the characteristics of the machines and/or in working cycles were the most relevant uncertainty components. The overall relative uncertainty p in WBV field assessment was in the range $14\% < p < 32\%$, whereas the relative uncertainty caused by transducer and measurement equipment in a correctly calibrated system is less than 4%.

1. Introduction

According to the EU Vibration Directive [1] the assessment of vibration exposure is based on the calculation of daily exposure $A(8)$ expressed as equivalent continuous acceleration over an 8 h period, calculated in accordance with ISO standard 2631-1 [2]. The sampling method adopted in the assessment must be representative of the personal exposure of the workers to mechanical vibrations. It is well known that large variations in vibration magnitude within a given class of vehicles can be found in field conditions [3,4]. Not properly taking into account all the factors which affect measurement uncertainty will result in an incorrect exposure assessment. The uncertainty in the evaluation of $A(8)$ daily vibration exposure is affected both by the uncertainty in the evaluation of vibration magnitude under field conditions and by the uncertainty in the evaluation of exposure duration.

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The extent to which these factors affect daily vibration exposure assessment can only be determined from field evaluations in different working places.

This study is a comprehensive evaluation of the relevant sources of uncertainty which affect $A(8)$ in specified working conditions.

2. Methods

Uncertainties associated with the field assessment of daily exposures to WBV were investigated in different working conditions for different categories of vehicles, including fork lifts, wheel loaders, garbage trucks, and buses. A total of 50 vehicles were included in the study in different field conditions: in marble quarries, marble laboratories, dockyards, paper mills, transportation and public utilities. Over 700 individual whole-body vibration (WBV) measurement analyses were performed. The data from all the measurements were grouped and analysed by vehicle, operator and working cycle.

The vehicles were operated by skilled drivers in typical field conditions during a set of working cycles which are representative of the main activities carried out at the working places investigated.

Table 1 shows the different categories of vehicles tested and the number of vehicles in each category.

2.1. Uncertainty evaluation

The uncertainty in the evaluation of daily vibration exposure $A(8)$ is affected by the uncertainty in the evaluation of vibration magnitude and by the uncertainty in the evaluation of exposure duration. The methods used to calculate measurement uncertainties are in accordance with the ISO publication "Guide to the Expression of Uncertainty in Measurement" [5], a reference standard in metrology [6,7]. Measurement uncertainties stem either from randomness or from systematic bias. The former are the so-called "Type A" uncertainties, and are evaluated by the statistical analysis of a series of observations. In this case the standard uncertainty is the experimental standard deviation of the mean obtained from an averaging procedure or an appropriate regression analysis. Systematic uncertainty, or "Type B" uncertainty, is evaluated from calibration data of the instrumentation used. To obtain the total uncertainty, the two uncertainty components are combined in quadrature.

In the conduct of field measurements of vibration exposure, the main factors determining type A uncertainty are:

1. Related to operators: Differences in the operators' anthropometric characteristics, posture and working methods. To take into account this issue, a single vehicle is operated in turn by different operators (see for example Table 2).

Table 1
Working places, number of typical working cycles and categories of vehicles investigated

Vehicle code	Vehicle type (no. of vehicles)	Working place	Working cycles (no. of different cycles)	Ground surface
1	Bus (12)	Liguria (Italy): transportation	Urban–suburban lines (8)	Asphalt
2	Fork lift (11)	Tuscany (Italy): paper mill	Loading/unloading/moving-paper boxes and paper cylinders (7)	Asphalt
3	Fork lift (8)	Tuscany (Italy): marble factory	Loading/unloading/moving marble slides (5)	Concrete/Asphalt
4	Fork lift (7)	Tuscany (Italy): dockyard	Loading/unloading/moving stone blocks (4)	Asphalt
5	Wheel loader (7)	Tuscany (Italy): marble quarry	Loading/unloading/moving marble blocks (4)	Marble
6	Garbage truck (5)	Tuscany (Italy): public utilities	Urban waste collection/ transportation to dump (3)	Asphalt

Table 2
Experimental conditions of repeated measurements used to estimate the three random uncertainty components $[(\sigma(a_w)_i]$ $(i = 1{,}3)$ (see Eq. (1))

Vehicle code	Component 1: Operator[a]	Component 2: Machine[b]	Component 3: Working cycle[c]	Number of individual a_{rms} measurements/axis
1	3 drivers/1 line/1 bus 9 a_{wrms} (10′) samples	12 different bus/1 driver/1 line 72 a_{wrms} (10′) samples	1 bus/1 driver 8 routes 32 a_{wrms} (10′) samples	103
2	3 drivers/1 working cycle/1 vehicle 9 a_{wrms} (10′) samples	11 vehicles/1 driver/1 working cycle 22 a_{wrms} (10′) samples	1 vehicle/1 driver/ 7 working cycles 7 a_{wrms} (10′) samples	38
3	3 drivers/1 working cycle/1 vehicle 9 a_{wrms} (10′) samples	8 vehicles/1 driver/1 working cycle 16 a_{wrms} (10′) samples	1 vehicle/1 driver/ 5 working cycles 5 a_{wrms} (10′) samples	30
4	3 drivers/1 working cycle/1 vehicle 9 a_{wrms} (10′) samples	8 vehicles/1 driver/1 working cycle 16 a_{wrms} (10′) samples	1 vehicle/1 driver/4 working cycles 4 a_{wrms} (10′) samples	29
5	3 drivers/1 working cycle/1 vehicle 9 a_{wrms} (10′) samples	8 vehicles/1 driver/1 working cycle 16 a_{wrms} (10′) samples	1 vehicle/1 driver/4 working cycles 4 a_{wrms} (10′) samples	29
6	3 drivers/1 working cycle/1 vehicle 9 a_{wrms} (10′) samples	5 vehicles/1 driver/1 working cycle 16 a_{wrms} (10′) samples	1 vehicle/1 driver/3 routes 3 a_{wrms} (10′) samples	28

Note:
[a]Component 1: Uncertainty related to changes in the operator's anthropometric characteristics, posture and methods of working.
[b]Component 2: Uncertainty related to changes in the characteristics and conditions of the machines used in working cycles.
[c]Component 3: Uncertainty related to changes in the characteristics of the travelling surface in typical working cycles.

2. Related to vehicles: changes in the characteristics and conditions of the machines used in working cycles: several vehicles of the same category—usually used to perform the same task—operated by the same driver and in the same working cycles are manned by a single operator in the same conditions (see, for example, Fig. 1).
3. Related to working cycles: changes in the characteristics of the travelling surface in typical working cycles: a single vehicle operated by a single driver is employed along several different paths. (see for example, Table 2).
4. Related to removing and re-positioning transducers: uncertainty associated to this operation was not evaluated separately: it is included in the overall uncertainty described at point 2 above.

The above mentioned type A components have been evaluated by the standard deviation of repeated measurements according to Table 2.

No influence due to the experimenter is expected or taken into account, as all the measurements were collected by the same two operators in accordance to a well defined protocol.

Systematic uncertainty—Type B—has been estimated on the basis of the characteristics of the instruments used, which conform to the requirements of International Standard ISO 8041 [8]: the margin of error acceptable within the standard leaves a typical uncertainty of the order $\pm 4\%$ in a correctly calibrated system, in the frequency range of the work vehicles which have been investigated. Calibration procedures adopted are described in the next section.

$A(8)$ relative uncertainty, defined as $\sigma(A8)/A(8)$, has been calculated applying the theory of error propagation of uncorrelated variables [6,7]:

$$\sigma(A8)/A(8) = \left[(\sigma(a_w)/a_w)2 + (0.5 \times \sigma(t_e)/t_e)^2\right]^{1/2}, \tag{1}$$

where

$$\sigma(a_w) = \left\{[(\sigma_1(a_w)]^2 + [(\sigma_2(a_w)]^2 + [(\sigma_3(a_w)]^2 + [\sigma_{\text{inst}}(a_w)]^2\right\}^{1/2},$$

$[(\sigma(a_w)]_{(i=1,3)}$ is the uncertainty on the frequency-weighted root-mean square (rms) value of the acceleration measurement, obtained by the standard deviation of repeated measurements (see Table 1). The index $(j = 1{,}3)$

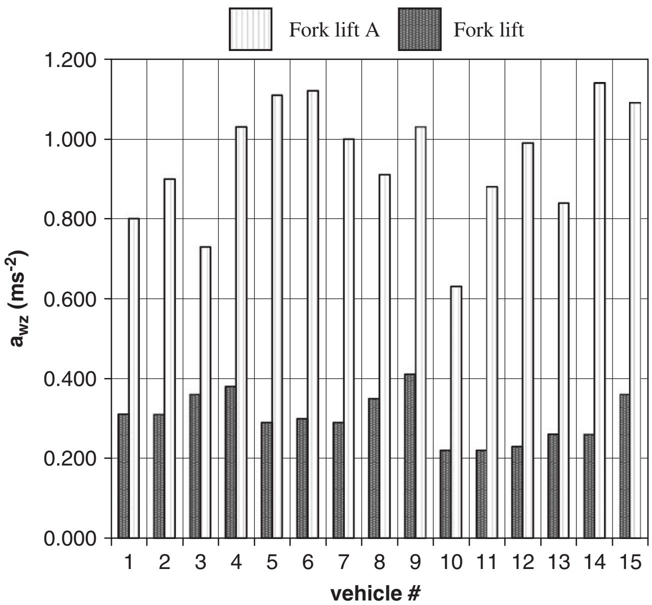

Fig. 1. a_{wz} values measured in different condition on two different typologies of fork lifts A and B in the following field conditions. Fork Lift A: Site of measurement: Paper mill: Same worker, same working cycle. 600 s measurement, 15 vehicles of similar characteristics. Mean $(a_{wz}) = 0.30\,\mathrm{m\,s^{-2}}$ St. dev. $= 0.06\,\mathrm{m\,s^{-2}}$. Fork Lift B: Site of measurement: Marble laboratory: Same worker, same working cycle. 600 s measurement; 15 vehicles of similar characteristics Mean $(a_{wz}) = 0.95\,\mathrm{m\,s^{-2}}$, St. dev. $= 0.15\,\mathrm{m\,s^{-2}}$.

refers to the three different Type A uncertainties reported above. $[(\sigma_{\text{inst}}\ (a_w)]$ is the systematic uncertainty on the frequency-weighted rms value of the acceleration due to instrument bias. t_e is the estimated exposure duration (these values can be either declared by workers or measured in the field). $\sigma(t_e)$ is the estimated uncertainty on t_e (direct observation); and a_w the mean value of the frequency-weighted rms acceleration (dominant axis).

The uncertainty in the estimation of exposure duration $\sigma(t_e)$ (Eq. (1)) has been evaluated in each working place by estimating the uncertainty of:

- exposure time supplied by the operators, by means of questionnaires administered to the workers. A questionnaire included, among others, the following questions:
  - Type of vehicle(s) used
  - hours/day
  - days/week
  - weeks/year
  - No. of years

    Exposure times, as reported by the workers, are defined in the present study as "nominal exposure times".
- variability of the working task from one day to another, by direct observation in the field.

  For each working day the following phases have been differentiated:
- waiting time (sitting in the vehicle–no vibration exposure)
- driving (working cycles and exposure conditions were specified)
- other activities outside the vehicle (no vibration exposure).

The durations of the different phases were evaluated for 7 working days by recording 360–480 daily observations (one every minute) with the use of a digital chronometer and assigning to each observation one of the phases above described.

2.2. Daily vibration assessment

Vibration was measured at the driver–seat interface in accord with the standard ISO 2631-1: a semi-rigid mounting disc (see ISO 10326-1 [9]) containing three axial ICP accelerometer PCB type 356B40 was used to measure vibration on the seat. To control artefacts due to self-generated transient vibration, which may influence measurement a three axis ICP accelerometer (PCB type 356B40) was used to measure vibration on the floor, close to the seat mount. The signals from the accelerometers were simultaneously acquired by a digital tape recorder DATATec-A80 Recal-Heim Systems GmbH (10 acquisition channels) and downloaded to a PC for post-analysis using software developed in Famos 4.0 IMC. The data were evaluated according to ISO 2631 [2]. The measurement chain conforms to the requirements of International Standard ISO 8041 [8]. The transducers are annually calibrated in accordance with ISO 5347 [10] and ISO 16063 [11].

The measurement chain was checked in the laboratory before and after field measurement using:

Vibration Calibration System TMS model 9100 C: Bandwidth 10–10 kHz; acceleration level: 1 g; accuracy $\pm 1\%$ (traceable to National Metrology System—annually calibrated).
Agilent 34401A Multimeter (traceable to National Metrology System, annually calibrated).

The uncertainty analyses have been performed using the most severe axis rms weighted acceleration value, calculated according to ISO 2631-1 [2].

Table 2 summarises the set of measurement durations, working cycles and operating condition selected in the individual WBV measurements to calculate uncertainty. In particular, to calculate the three uncorrelated random uncertainties indicated in the relationship (1) the following sets of repeated measurements have been carried out:

1. Operator related uncertainty: repeated measurements in the same working cycle and same vehicle operated by three different drivers. Transducers were not removed.
2. Vehicle related uncertainty: repeated measurements on different vehicles of the same category which are usually used to perform the same task, operated by the same driver and in the same working cycles. Transducers were removed and re-positioned: the uncertainty associated to this operation is included in the overall uncertainty evaluated in this set of repeated measurement.
3. Working cycle related uncertainty: repeat measurements on more working cycles performed by the same machine and by the same operator, in a different area of the site where the working cycle is usually performed. Transducers were not removed.

To reduce artefacts due to self-generated transient vibration which may influence measurements, each operator was instructed to be careful when altering position during travelling. To avoid artefacts due to sitting down into the seat, the data acquisition started 1–2 min after the ingress of the operator in the vehicle. In the post-processing phase, the presence of artefacts due to altering position during travelling has been identified by comparison of the vibration simultaneously recorded in a rigid point outside the seat pad, close to the seat mount. If the transient recorded by the seat accelerometer (in the seat pad) did not show up in a point outside the seat pad, it was assumed that the transient originated from the operator's movements. In this case it was removed from the time record used in the $a_{w\mathrm{rms}}$ calculation.

3. Results

The uncertainties of daily vibration exposure arising from the different uncertainty sources affecting $A(8)$ estimations are reported in Table 3 for the operator, vehicle, working cycle, instrumentation, exposure time. Table 4 reports exposure time results from direct observation in the field.

In all the field conditions investigated, changes in the characteristics of machines and/or working cycles were the most relevant uncertainty components. The overall percentage uncertainty, p, in WBV field assessment was in the range $14\% < p < 32\%$. Uncertainty in exposure time due to the variability of the working task from one day to another, as measured by direct observation in the field, was in the range 0.3–1 h, with a relative

Table 3
Results of the measured uncertainties affecting $A(8)$ estimation in different vehicles

Vehicle code	a_w[a] ($\mathrm{m\,s^{-2}}$)	σ_1 (%)[b]	σ_2 (%)[c]	σ_3 (%)[d]	σ(instr.) (%)	$\sigma(t_e)$ (%)	σ ($A(8)$) (%)
1	0.30	7.4	26.5	15.1	4.0	5.5	31.8
2	0.30	5.5	17.0	14.0	4.0	12.5	24.1
3	0.95	8.8	9.8	14.4	4.0	12.5	20.8
4	0.40	6.3	25.0	9.8	4.0	12.5	28.7
5	0.35	7.4	27.5	9.7	4.0	12.5	31.1
6	0.30	5.2	10.3	5.3	4.0	8.0	14.2

Note:
[a] a_w: rms weighted acceleration value -maximum exposure axis, according to ISO 2631.
[b] σ_1 (%): Percentage uncertainty related to changes in the operator's anthropometric characteristics, posture and methods of working.
[c] σ_2 (%): Percentage uncertainty related to changes in the characteristics and conditions of the machines used in working cycles.
[d] σ_3 (%): Percentage uncertainty related to changes in the characteristics of the travelling surface in typical working cycles.

Table 4
Exposure time variability measured by direct field observation

Vehicle code	Working activity	Exposure time measured t_e ($\mathrm{h\,day^{-1}}$)							Average exposure time ($\mathrm{h\,day^{-1}}$)	"Nominal" exposure time ($\mathrm{h\,day^{-1}}$)
1	Bus driving	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Mean ± s.d.	Declared by the worker
2	Fork lift: moving/loading at paper mill	5.3	5.7	5.6	5.7	5.2	5.9	6.2	5.6 ± 0.3	6
3	Fork lift: moving/loading at marble factory	5.1	4.8	4.9	6.0	5.1	5.6	6.9	5.5 ± 0.7	5.5
4	Fork lift: moving/loading at dockyard	6.5	4.3	4.9	5.2	4.5	5.5	5.0	5.1 ± 0.7	5.5
5	Wheel loader: moving loading at marble quarry	6.9	6.3	8.5	7.2	6.5	8.1	6.4	7.1 ± 0.8	8

uncertainty in exposure time in the range 5–13%. Higher values were related to the variability of working tasks occurring in some working activities, such as loading operations using fork lifts, whereas the exposure times of bus drivers show less variability (see Table 4). Therefore, the contribution of time exposure uncertainties to the overall uncertainty was in the range 1–5%.

4. Discussion

The variability of WBV measurements is often mentioned in the literature: CEN Standard 14253 [4] prescribes that "*the experimenter shall determine the main sources of uncertainty and multiple measurements shall be made in order to determine the extent of the uncertainty and to calculate the standard deviation regarding the dominant sources of uncertainty*". Despite this, there has been few studies to quantify this variability in field conditions, to lead to a realistic picture of the daily exposure of a subject and of the relevant uncertainties [3,12,13].

This study showed that in all the field conditions investigated, changes in the characteristics of machines and/or in working cycles were the most relevant uncertainty components of vibration exposure in field condition.

The EU Vibration Directive prescribes among the "*Provisions aimed at avoiding or reducing exposure*", "*appropriate maintenance programs for work equipment*". The high variability associated with the "vehicle component uncertainty'' in the present study confirms the importance of programming regular maintenance of vehicles into the strategy for evaluating and reducing risks.

Variability related to working cycles highlights the importance of conducting an appropriate task analysis prior to performing vibration assessments at a workplace, to analyse adequately the different exposure conditions of subjects, and to perform a correct vibration exposure estimation.

The study found that the contribution of exposure time uncertainties to the overall uncertainty was in the range 1–5%. These values indicate that in many cases it is possible to simplify the process of estimating daily vibration exposures without introducing relevant errors in the $A(8)$ estimation by treating exposure time as ''nominal values''.

5. Conclusions

The study made it possible to isolate major sources of uncertainty in field assessments of daily exposures to WBV. Experimentation revealed that in all the field conditions investigated, changes in characteristics of machines and/or in working cycles were the most uncertain components. The overall percentage uncertainty, p, in WBV field assessment was in the range $14\% < p < 32\%$, whereas the percentage uncertainty caused by transducer and measurement equipment in a correctly calibrated system is $<4\%$.

Incorrect $A(8)$ estimation could arise if uncertainty components are not taken into account in the process of field assessment of daily exposure to WBV.

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References

[1] Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC.
[2] International Organization for Standardization, ISO 2631-1, Mechanical Vibration and skock—Evaluation of human exposure to whole-body vibration Part 1: General requirements, 1997.
[3] G.S. Paddan, M.J. Griffin, Vibration exposure in vehicles, *Journal of Sound and Vibration* 253–1 (2002) 195–213.
[4] European Committee for Standardization, Practical guidance. EN 14253 Mechanical vibration–Measurement and evaluation of occupational exposure to whole-body vibration with reference to health, 2003.
[5] International Organization for Standardization, ISO, Guide to the Expression of Uncertainty in Measurement, 1995.
[6] European Co-operation Accreditation, EA-4/02 Expression of the Uncertainty of Measurement in Calibration, 1999.
[7] Jhon.R. Taylor, *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*, University Science Books, CA, USA, 1997.
[8] International Organization for Standardization, ISO 8041, Human response to vibration–Measuring instrumentation, 1993.
[9] International Organization for Standardization, ISO 10326–1, Mechanical vibration. Laboratory method to evaluating vehicle seat vibration—Part 1: Basic requirements, 1992.
[10] ISO 5347 (all parts), Methods for the calibration of vibration and shock pick-ups, 1993.
[11] ISO 16063 (all parts), Methods for the calibration of vibration and shock transducers, 1998.
[12] N.J. Mansfield, S. Atkinson, G. Payne, Effect of increasing measurement duration on 'accuracy' of whole-body vibration field measurements, *Proceedings of 38th United Kingdom Conference on Human Response to Vibration*, 2003, pp.1–11.
[13] P. Pitts, Uncertainty in evaluating exposure to hand-transmitted vibration, *Acoustics Bulletin* 28 (5) (2003).