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MEASUREMENTS FOR THE EVALUATION OF VIBRATION EXPOSURE OF OPERATORS IN A SHIP CONTAINER TERMINAL

Francesco Crenna , *Giovanni B Rossi*

Università degli Studi di Genova – DIMEC, Genova, Italy, crenna@dimec.unige.it

Abstract – The measurement of the vibration transmitted to the human body is key for the prevention of the risk of spine damage, in the long run, for operators of industrial vehicles. Even if no such risk exists, such information is important for assessing the comfort and, consequently, for ensuring proper ergonomic conditions. In this paper we discuss important issues concerning the measurement of vibrations transmitted to operators' by vehicles used for moving and handling containers in a maritime terminal. Sensor installation is considered, with particular attention to interfacing problems, proposals for improving the reliability of the measured values are presented and factors influencing the variability of measurement results are analysed. Lastly, experimental results are presented and discussed, with particular attention to characterising parameters used for exposure evaluation.

Keywords : Measurement for safety, Vibration testing, Industrial statistics.

1. INTRODUCTION

The European Directive 2002/44/CE [1, 2] requires the evaluation of the worker's exposure to vibrations on the basis of specific in-field measurements or referring to values available in data bases. In any case, measurement uncertainty is a key factor, affecting the decisions to be taken. In the specific case of vehicles for container handling in a maritime terminal, there are many influence quantities affecting the results [7-13]. There are both internal influence quantities, i.e., due to the vehicle itself, such as machine and operator's seat characteristics, and external ones, such as the road pavement and the driving style. In currently available data bases [8], as in literature, it is very rare to find indications about the most important influence factors and their quantitative evaluations [9]. In reality, some studies regarding variability can be found in literature, but they refer to very specific cases, from which it is difficult to generalise.

In this paper we present an approach to the design and realisation of the measurement campaign, with the specific aims of limiting as much as possible the dispersion of the results and of guaranteeing their reliability. After an introduction to the relevant parameters of the vibration phenomenon, we outline the main features of the test-case environment. Then we present the design of the testing procedure and of the measuring system. We discuss in particular the use of redundancy for achieving maximum reliability. Lastly, we consider the statistical analysis of data and provide recommendations.

2. NORMATIVE REQUIREMENTS AND RELEVANT PARAMETERS

The recommended methodology for assessing the level of exposure for *whole body vibration* (WBV) is specified in Ref. [3]. Acceleration measurements have to be carried out by using triaxial sensors and proper adapters, in order to place them at the interface between the operator's body and the vibration source, without any substantial alteration of the transmission path. Then, measurement signals must be frequency weighted, to account for the characteristics of human response [3-6], by proper filtering procedures.

Vibration exposure is mainly characterised the weighted root mean square (r.m.s.) acceleration, for each motion axis, that is

$$a_{w,i} = \sqrt{\frac{1}{T}\int_0^T \left[a_{w,i}(t)\right]^2 dt} \ \ [\mathrm{m \cdot s^{-2}}],$$

where is the frequency-weighted acceleration referred to the *i-eth* axis, $a_{w,i}$ is its root mean squared value and T is the observation time. Exposure assessment may be done by considering the highest acceleration value among the three axis, with an additional correction factor, that amplifies the contribution of the vibrations along horizontal axes:

$$A_{w\max} = \max\left\{1,4 \cdot a_{w,x}, 1,4 \cdot a_{w,y}, a_{w,z}\right\} \ \ [\mathrm{m \cdot s^{-2}}],$$

where z is the vertical axis, and the horizontal plane xy is positioned on the seat plane of the operator.

Finally, in order to be able to compare different working conditions it is necessary to refer the exposure to a standard period of 8 working hours. This normalised value, denoted by *A(8)* may be obtained by

$$A(8) = A_{w\max}\sqrt{\frac{T_e}{8}} \ \ [\mathrm{m \cdot s^{-2}}],$$

where T_e is the exposure time. The formula is based on the application of the equal energy principle, which assumes that health effects of vibration is mainly related to the "energy" (that is the integral of the quadratic value) of the weighted acceleration signal [6, 21]. When impulsive phenomena are present, additional parameters must be considered [3], to account for the effect of acceleration peaks: we will briefly mention them in the discussion of experimental results.

3. THE WORKING ENVIRONMENT

A maritime container terminal is the environment where containers are transhipped between ships and land vehicles. A container may have a length of 6-12 m. A common conventional unit for the container capacity is the Twenty-foot Equivalent Unit (TEU). The maximum load capacity for 1 TEU containers is about $20 \cdot 10^3$ kg. Containers are to be moved as quickly as possible, and of course at the lowest cost. The key activities in the terminal are

1) the unloading of containers from ships to the land storage area,
2) the loading of containers from the storage area to ships,
3) the movement of containers in the storage area and
4) the loading – unloading of private trucks or trains.

(a) (b) (c) (d)

Figure 1 – Container handling vehicles: (a) portainer, (b) tractor, (c) straddle crane, (d) reach stacker.

Vehicles used for these purposes include (figure 1)

- *portainers*, i.e., dockside cranes for handling containers, designed for a quick loading and downloading from the ships to the land,
- *straddle cranes*, which are self propelled gantry cranes that move on rubber tires or rails (Rubber Tired Gantry–RTG and Rail Mounted Gantry–RMG), used for the movement and positioning of containers in a storage yard,
- *reach stackers*, having a greater speed and manoeuvrability than straddle cranes, but able to reach a limited height and
- *tractors,* the most common vehicles for the movement of containers within the storage area.

4 TESTING AND MEASUREMENT STRATEGY

The testing goal is to obtain a reliable measure of the acceleration level and a characterisation of its variability. To achieve these aims, we proposed a measurement procedure including the following steps:

- the definition of a standard working cycle [20] representative of the normal working activity;
- the recording of the whole set of influence quantities, in order to enable an analysis of variance;
- the installation of redundant sensors, in addition to those required by the norms [3-5], along the vibration transmission chain of the operator seat, to overcome interface problems [11], to identify eventual anomalous measurements and to characterise the operator's seat behaviour;
- the definition and application of a procedure for the verification of the measurement chains, including checks with reference sensors and portable calibrators, before, during and after measurements;
- proper data processing, for optimum use of the available information, including redundancy and *in situ* calibration data.

Concerning the measurement strategy the following points have to be considered:

- to optimize the number of measurements to be carried out,
- to maximise the information available from the measurements,
- to reduce overall measurement uncertainty and
- to evaluate measurement variability.

The first two points aim at maximising the efficiency of the measurement campaign, to limit its impact to the normal working activity and limit costs. Of course measurement uncertainty affect the reliability of the results, while a good characterisation of the variability causes and their effect may be useful when assessing the risk. These four points enable a deep investigation of the vibration phenomenon, for a reliable risk assessment.

Concerning WBV measurements, in docks environment a critical aspects is represented by the repeatability and reproducibility of measurements due to the intrinsic variability of the measurand. The measurement strategy should provide useful preventive actions to limit all the variability causes, but some trade off is necessary, since measurements have to be carried out during the normal operation of the terminal. In this regard, we proposed to define a general *standard working cycle*. The introduction of a standard working cycle allows to refer the measurement to similar conditions and makes the interpretation of the measurement results and the risk assessment clearer and more reliable. From an operative point of view, considering the usual working procedure in the terminal, the standard working cycle can be defined for all the vehicles involved in this study as follows:

- movement without load to reach the loading area/point;
- loading operation;
- movement with load to reach the unloading area/point;
- unloading operation.

Moreover, for each machine typology several models are present, with several units, often with different ageing periods. In principle, a good implementation of the strategy itself enables the investigation of these influence quantities on the vibration value not only for the different vehicles, but also for different models or different units. From the experimental point of view, we have decided to test all the main handling vehicles used in the terminal, as presented in paragraph 3, under different loading conditions, and operated by several operators, even if it was not possible to get the same level of detail for all the conditions.

It is known in the literature [9, 16, 18] that the vibration measurement for the evaluation of WBV, carried out in the field, is critical not only for the effect of influence quantities, as already discussed, but also from the instrumental standpoint, with particular reference to the installation of the sensing elements. For this reason, a validation procedure has been planned and conducted on three levels:

i) a preliminary verification in the laboratory,

ii) an on-site calibration, after the set up of all the measurement chains and

iii) a validation during the data processing phase.

In the first phase the complete measurement chain is verified in the lab by comparison with a reference measurement chain on an electrodynamic shaker. On site it was possible to record the vibration level from a portable calibrator (B&K 4231), before and after carring on the measurements. During the processing it was possible not only to check these reference values but also to compare the recorded signals from independent sensors positioned in the same place on the seat.

In our opinion this approach may be effective in minimising measurement errors due to both instrumentation and measurement condition anomalies, and in guaranteeing the reliability of the measurement data and, consequently, of risk evaluation.

5 THE MEASURING SYSTEM

Two independent measuring systems have been used. The first consists of an advanced vibration analyser (Soundbook®), based on a data acquisition system and a rough portable personal computer, with dedicated software (Samurai®). The instrument acquires data from a triaxial accelerometer mounted in a flexible disc to measure vibrations transmitted through the seat, and from an additional monoaxial transducer placed in the rigid structure just under the seat. The second measuring system is a modular measurement chain, based on a National-Instruments PXI system. It is connected to signal conditioners for a triaxial and a monoaxial accelerometer. The sensors positioning along the seat structure, the same for all the measurements, is presented in figure 2.

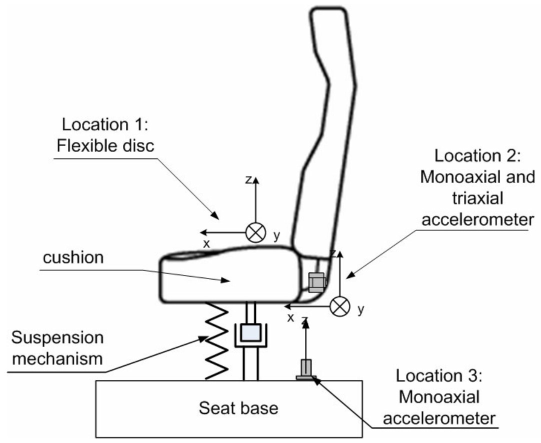


Figure 2 – Installation of sensors on the seat frame.

This layout allows the monitoring of vibration in the following points:

- the cabin floor or the rigid structure, fixed to the floor and supporting the seat, with its suspension system,
- the rigid structure above the suspension system, which supports the foam seat and
- the driver seat interface.

This rather simple way of proceeding is by itself able to guarantee a high level of reliability of the measurement results. Redundancy in the measurement equipment allows comparison of the acceleration data acquired by different transducers. *In situ* calibration ensures the correctness of the sensitivity and is able to evidence possible thermal variations.

6 EXPERIMENTAL RESULTS AND DATA PROCESSING

The vehicles have been driven by skilful operators carrying out a set of working cycles, representative of the main activities under normal working conditions.

The total duration of each measurement was based on the standard working cycle of the investigated vehicles: from a minimum of less than a minute (for example in the case of an RTG) up to a maximum of more than 10 minutes (in the case of the tractor). For each typology of vehicles several recordings have been performed for a total amount of more than 170 time histories.

The software of the vibration analyser provides directly the values for the overall characterisation of the working conditions. For processing the signals from the custom instrument, we have written a code in the Matlab® environment. After a pre-processing procedure, some parameter are evaluated, such as frequency-weighted r.m.s., power spectral densities, and root–mean–square acceleration levels in one–third octave bands, the crest factor etc. as we have mentioned, current norms consider additional special parameters, when impulsive phenomena are dominant. There is discussion in the scientific community [17-19] about the suitability of such additional parameters, so that in some cases the national regulations do not require their use. This is for example the case of the Italian legislation that acknowledges the EU Directive [2]. For completeness of investigation the code that we have implemented, calculates also the additional parameters

$$VDV = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \text{ [m·s}^{-1,75}\text{]},$$

$$MTVV = \max \left\{ \sqrt{\frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left[a_w(t) \right]^2 dt} \right\} \text{ [m·s}^{-2}\text{]},$$

where a_w is the weighted acceleration measured along each axis, as well as the running rms value; see Ref [3], for a discussion. All these analyses are carried out for each acceleration sensor.

One of the main goals of this study was the investigation of measurement variability. The study is based on a wide experimental campaign consisting of more than 200 recordings. The most significant acquisitions are illustrated in table 1.

Table 1: data availability for each type, model and item investigated.

VEHICLE TYPE	MODELS	ITEMS	NUMBER OF ACQUISITIONS
Tractor	2	2+4	37
RMG	2	2+4	60
RTG	1	2	20
Portainer	1	4	39
Reach stacker	3	3	20

Table 2 presents the relative variability for all the measured vibration parameters. It is worth noting that such a variability has been observed after having implemented a measurement strategy, including a standard working cycle, designed with the main purpose of the reduction and control of measurement variability.

Table 2 – Variability of vibration parameters along the z axis, in terms of relative standard deviation

VEHICLE	a_{wrms} [%]	*CF* [%]	*MTVV* [%]	*VDV* [%]
Tractor	31	29	35	26
RMG	20	41	31	35
RTG	24	34	24	26
Portainer	63	38	52	57
Reach stacker	26	37	29	26

From these data it appears that, in our case, when dealing with transient vibration parameters such as *VDV* or *MTVV*, since they take much in consideration the transient impulsive components in the signal, they present a much higher variability than the standard r.m.s. values. Even if this is a particular and specific application, we consider it as well representative of the general situation a vibration investigator have to face when dealing with measurement carried out during the normal working activities, above all if carried out onboard of vehicles.

Figure 3 presents the rough time history and the running r.m.s. for the vertical weighted accelerations measured on the seat in a tractor. The rough plot shows the presence of several impulsive events: in these cases, if the crest factor exceed 9, the ISO standard suggests two additional quantities for the assessment. The behaviour of the running r.m.s. of the acceleration, evaluated with 1s time constant, is presented in (b). Since the *MTVV* is defined as the highest value of the running r.m.s., it is clear that a sporadic transient vibration event can alter the correct assessment of vibration exposure. The decision regarding the consideration of these high peaks are left to the judgment of the investigator and can result in misleading conclusions.

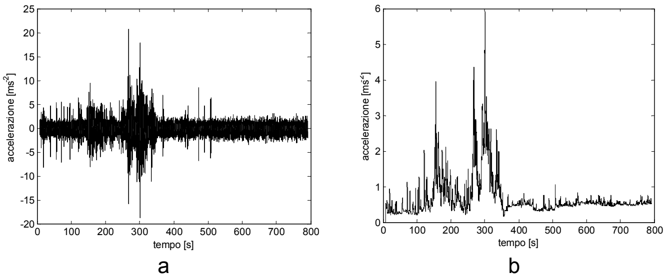


Figure 3 – Acceleration along z axis: rough time history (a) and running r.m.s. (b), for a tractor.

It is also possible to provide such an analysis for all the sensors placed along the seat of the vehicle considered, enabling the identification of impulsive events not due to the machine behaviour but to operator's movements on the seat.

Of course the operator may need to adjust his position on the seat or to move in order to manage to load or unload operations. These movements, when carried out roughly, can produce peaks in the signals affecting the evaluation of all the parameters. The proposed redundant set up, enables the investigator to assess if the peak is due to a vibration coming from the floor of the cabin and moving toward the operator through the seat or directly generated on the seat by the operator himself, as shown in figure 4. Moreover, the redundancy along the seat enables an evaluation of the seat behaviour, giving, as a side effect, the indication for the substitution and some good information regarding the frequency behaviour to be required for.

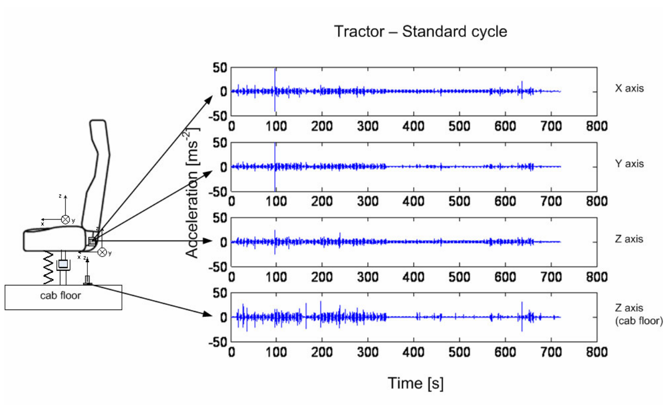
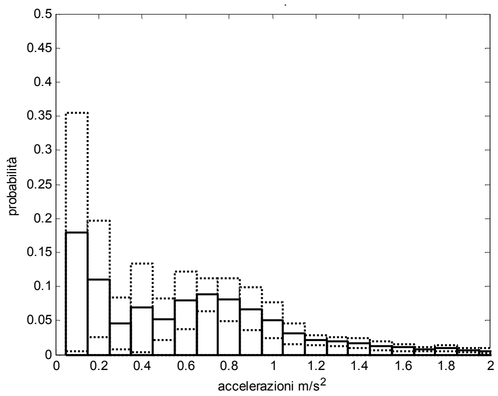
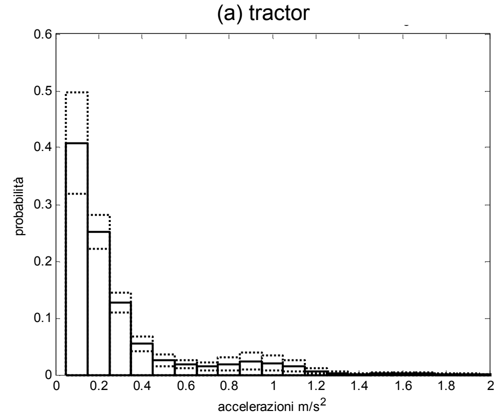


Figure 4. Vertical acceleration time histories from sensors along the seat structure. Peak around 100 s is present on the seat only.

The flexible processing approach we considered enabled us to further investigate the working situation for example with a statistical approach. By considering the running rms value it was possible to divide the acceleration time history in small windows and to evaluate for each recording the distribution of the rms values in time. An example of such an approach is given in figure 5 for two machine types. The difference in the shapes of the probability distribution is evident and each shape has been shown as characteristics of each machine type.



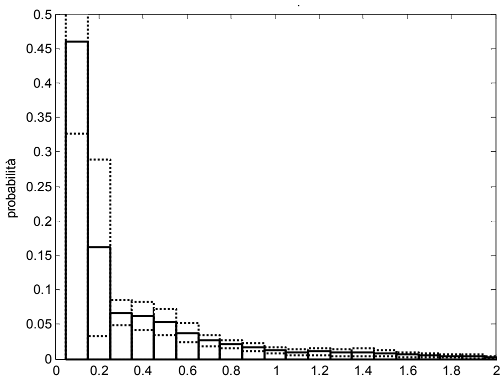
(a) tractor



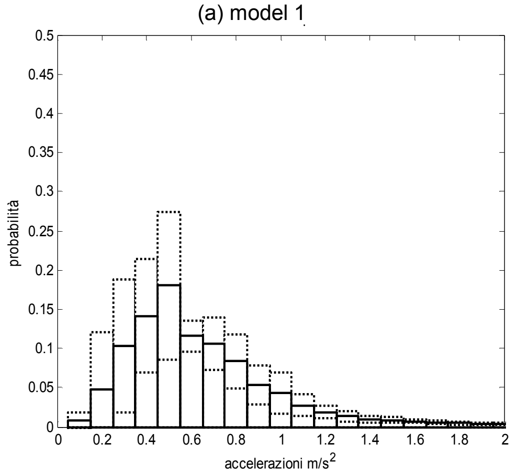
(b) portainer

Figure 5. Distribution of the acceleration values for different machine types.

Beside that it is possible to compare the distributions among different models of the same type, as presented in figure 6. If a difference is shown this is due to the mechanical behaviour of the specific model. So this information can be exploited when purchasing new machines.



(a) model 1



(b) model 2

Figure 6. Distribution of the acceleration values for different models of the same machine type.

The graphs presented shows the distributions with the indication of the variability for each probability level in a two fold sigma representation. It is interesting to note that there is a good stability in the distribution behaviour, mainly at high levels, showing the reliability of these results.

A more detailed analysis of such distribution shows, in several cases, a dominant contribution of the low acceleration levels. Since our measurement have taken place during the normal operating activity, even if according to a standard cycle, often the operators have to wait onboard the machine with the engine on and ready to operate, for the loading or unloading operation, due to the traffic or unavailability of the loading machine.

From this point of view, in our opinion, this statistical approach can be very useful for example to assess the frequency of high acceleration events, and to evaluate the low level contribution to the overall exposure.

On this basis at the moment we are proceeding with a further processing regarding the analysis of several influence quantities on the overall parameters and on the distributions themselves. Such quantities have been recorded for each acquisition even if we had no control over them. As an example we can consider the length of the container to be handled and its weight, or the operator behaviour and so on.

4. CONCLUSIONS

The paper considered the problem of the measurement of vibration transmitted by moving machines to the operator's body, with application to the dock environment.

The paper presented a proposal for a measurement procedure designed to control and characterise the variability of the measurements in order to guarantee proper values for exposure and following risk evaluation.

The procedure requires the definition of a standard cycle that may be implemented in the normal operability, the recording of all the uncontrollable quantities, the use of proper metrological verification procedures.

The measurement strategy requires the measurement of several machine models and items in order to depict a complete scenario of the possible working situations.

A measurement system based on two independent instruments and a set of redundant sensors placed along the seat enables a cross validation of the measurement and the verification of both the source of vibration and seat behaviour.

The proposed measurement set up and procedure was implanted for measurement onboard four types of machines used for container handling in the docks. Several models for each types and several items for each model were measured under different conditions, such as the load weight or type.

The proposed approach has shown to be effective for as regards the capability to gather detailed reliable information in an efficient way. Signal processing has shown that even if trying to control as much influence quantities as possible with the proposed procedure, since the measurement were carried out during normal operability, they still present a high variability, especially when additional parameters for impulsive events are evaluated. This confirms the key importance of variability evaluation and the main role of measurements in this kind of investigations.

The flexible processing tool we developed enabled us to propose a statistical approach showing the probability distributions of the acceleration levels for different machine types and models. Such an approach seems to be promising in order to improve the reliability of the exposure evaluation. Beside that this tool can be used to characterise the machine model behaviour identifying the best choices for future replacements.

Further investigation will regard some practical proposals regarding the use of such distributions, and an analysis of the variance of both the overall parameter and the distributions.

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