International Journal of Industrial Ergonomics 52 (2016) 59–68

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Predicting whole-body vibration (WBV) exposure of Malaysian Army three-tonne truck drivers using Integrated Kurtosis-Based Algorithm for Z-Notch Filter Technique 3D (I-kaz 3D)

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ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form
29 June 2015
Accepted 23 August 2015
Available online 9 September 2015

Keywords:
Whole-body vibration (WBV)
Malaysian Army (MA) three-tonne trucks
Integrated Kurtosis-Based Algorithm for Z-Notch Filter Technique 3D (I-kaz 3D)
Vibration dose values (VDV)
Regression models

ABSTRACT

The objective of this study is to present a new method for determination of whole-body vibration (WBV) exposure in the driver's seat of Malaysian Army (MA) three-tonne trucks based on changing vehicle speed using regression models and the statistical analysis method known as Integrated Kurtosis-Based Algorithm for Z-Notch Filter Technique 3D (I-kaz 3D). The study was conducted on two different road conditions; tarmac and dirt roads. WBV exposure was measured using a Brüel & Kjær Type 3649 vibration analyser, which is capable to record WBV exposures from the driver seat and vibration from the truck, and comparisons were made between the two types of roads. The data was analysed using I-kaz 3D to determine the WBV values in relation to varying speeds of the truck and to determine the degree of data scattering for WBV data signals. Based on the results obtained, WBV exposure levels can be presented using frequency weighted root mean square (RMS) accelerations (a_w), vibration dose value equivalent to 8 h (*VDV(8)*), I-kaz 3D coefficient ($\mathcal{Z}^{\infty}_{3D}$) and the I-kaz 3D display. The I-kaz 3D displays showed greater scatterings, indicating that the values of $\mathcal{Z}^{\infty}_{3D}$ and *VDV(8)* were getting higher. The prediction of WBV exposure was done using the developed regression models and graphical representations of $\mathcal{Z}^{\infty}_{3D}$. The results of the regression models showed that $\mathcal{Z}^{\infty}_{3D}$ increased when vehicle speed and WBV exposure increased. For model validation, predicted and measured noise exposures were compared, with high coefficient of correlation (R^2) values obtained, indicating that a good agreement was obtained between them. By using the developed regression models, we can easily predict WBV exposure in the driver's seat for WBV exposure monitoring.

1. Introduction

In a variety of military vehicles, whether at sea, air or land, soldiers would feel uncomfortable due to vibration produced by the movement of the vehicles. There are many sources of vibrations, such as engine, wind, chassis and road-tire interaction. Vibration causes excitations to the chassis structure, which is transmitted via mechanical vibrations into the driver's compartment, where they can be felt as vehicle interior vibrations in the seat, steering wheel and / or body floor (Aziz et al., 2014a). Since drivers are often exposed to vibration for a long time, the effect of vibration characteristics on the human body have been the subject of interest in many studies (Li et al., 2015).

Apart from that, exposure to whole body vibrations (WBV) is common, primarily when the work requires the operation of heavy vehicles such as buses, trucks, forklifts and heavy machinery (Costa et al., 2014). WBV refers to the situation where the whole body is exposed to vibration through contact by the buttocks or feet. Vibration exposure depends on several factors, such as type and design of the vehicle, speed, environmental conditions and driver posture (Nakashima and Cheung, 2006). When driving, a Malaysian Army (MA) driver sits for a long time on the surface of the seat, which, along with steering wheel, will vibrate and cause discomfort. This discomfort will cause musculoskeletal disorders (MSD), fatigue and exhaustion, and severe health disorders, and affect

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http://dx.doi.org/10.1016/j.ergon.2015.08.008
0169-8141/

human performance. Exposure to WBV is one of the physical hazards that give rise to long-term adverse health effects, particularly MSD, among the army personnel handling the armoured vehicles. In Malaysia, military armoured vehicle drivers are qualified drivers who are specifically trained to drive the armoured vehicles. They must be medically healthy, fit and ready to be deployed at all times. Any MSD related to long-term WBV exposure, such as low back pain (LBP), the most common type MSD (Thamsuwan et al., 2013), might affect their strength, active duty time and capability, as well as occupational performance (Rozali et al., 2009).

Various international standards have been developed in which human vibration should be measured and reported, as well as provide indications of the health risks involved. The European Parliament legislation stipulates minimum standards for health and safety of workers exposed to WBV, in terms of exposure action value (EAV) and exposure limit value (ELV) associated with 8 h of daily exposure, in addition to requiring employers to reduce worker vibration exposure levels wherever it is practically possible (Directive 2002/44/EC). Previous studies on Malaysian Armed Forces (MAF) tactical vehicles by Aziz et al. (2012) and military tracked armoured vehicles by Rozali et al. (2009) found that WBV on the driver seat exceeded EAV, which is 0.5 ms^{-2} or 15 $ms^{-1.75}$, which indicated that precautionary steps should be taken as the WBV value has nearly reached the ELV, which is 1.15 ms^{-2} or 21 $ms^{-1.75}$. Data analysis from these studies was done by comparing the obtained WBV values with the daily EAV and ELV values based on Directive 2002/44/EC. Other MA vehicles (Aziz et al., 2008, 2012; Khan et al., 2010) were also tested, with fairly high discomfort reported based on the comfort reactions to the vibration environment table in ISO 2631-1: Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration, Part 1 – General Requirements (ISO, 1997). These studies proved that all the drivers felt uncomfortable with the WBV generated from all the different types of tested vehicles.

Various studies on WBV model development have been conducted by many researchers in order to estimate or predict WBV exposure from vehicles. Daruis (2010) developed an integrated model for measuring and evaluating the level of discomfort for car seats of passenger vehicles in Malaysia. The model included parameters of discomfort sensation, and static and dynamic modalities. Cann et al. (2004) evaluated variable predictors, such as road condition, truck type, driver experience, truck mileage and seat type, for WBV exposure experienced by highway transport truck operators. The results showed that road condition was a significant predictor ($p < 0.01$) of the frequency-weighted root mean square (RMS) accelerations for all three axes (*x*, *y* and *z*) and the vector sum of the axes. Chen et al. (2003) also developed WBV predictors, such as personal factors, vehicle characteristics and other occupational activities. Based on these identified WBV predictors, a statistical instrument was developed for WBV exposure assessment for subjects without direct WBV data in order to examine the exposure-response relation between WBV and low back disorders. Nopiah et al. (2012) developed a vehicle acoustical comfort index (VACI) and vibration dose values (*VDV*) to evaluate the noise annoyance and vibration levels respectively in passenger car cabins. Using the change trend of the noise and vibration levels depending on engine speeds, an optimisation model was proposed for the vibration level in the passenger car cabin. From this observation, it was concluded that the more vibration produced, the more annoying is the noise. In addition, using the models, the researchers were able to estimate the maximum level of vibration to be achieved in order to obtain better VACI values for pleasant sound in the car cabin interior. Rahmatalla and Deshaw (2011) predicted discomfort due to non-neutral head-neck postures for ten seated subjects who were subjected to WBV in the fore-aft direction using variable discrete sinusoidal frequencies, and their subjective responses were recorded using the Borg CR-10 scale. The results showed that the subjective-reported discomfort increased for the head-down posture, and decreased for the head-up and head-to-side postures. Village et al. (2012) modelled WBV exposure from a number of observed and self-reported variables. Despite a large number of variables included in the model (34) and 54 worker-days of WBV measurement, the final models contained only four variables, which explained 60% of the variance. The variables were vehicle speed (<20 kmh^{-1} and/or 20–40 kmh^{-1}), backrest adjustment, vehicle type and industry. However, the statistical models were not univocal because according to the requirements, a more complex application was required with higher accuracy in the predictions (Nitti and De Santis, 2010).

The objective of this study is to present a new method for determination of WBV exposure in the driver's seat of MA three-tonne trucks based on changing vehicle speed using regression models and the statistical analysis method known as Integrated Kurtosis-Based Algorithm for Z-Notch Filter Technique 3D (I-kaz 3D). This study was conducted by examining the relationship between vibration dose value equivalent to 8 h (*VDV(8)*) and I-kaz 3D coefficient ($\mathscr{Z}^{\infty}_{3D}$). Previous studies concerning the relationship between *VDV(8)* and $\mathscr{Z}^{\infty}_{3D}$ were conducted by Ismail et al. (2012) and Aziz et al. (2014b). For these studies, only tarmac roads were used as the test site. Therefore, differences of WBV exposure due to different road surfaces could not be studied by them. Furthermore, Ismail et al. (2012) only recorded vibrations at two speeds, 30 and 60 kmh^{-1}. More speeds, including stationary, should be recorded so that the trends of vibrations with the different speeds can be seen very well. Aziz et al. (2014b) used a different triaxial accelerometer type, with the overall vibration levels in each axis being recorded. This study's I-kaz 3D analysis requires time discrete continuous raw data from the time domain graph rather than just overall vibration levels. In addition, there are other weaknesses in the study such as the test site has been carried out for tarmac road only, there is no comparative results for dirt road frequently travelled by this type of truck. Then, only one truck was tested and it is not enough to develop a reliable WBV exposure model and developed correlation equations can be questionable for use in predicting the WBV exposure from other vehicles. Moreover, VDV result for each truck speed was recorded just a repetition of reading only and is not repeated at least 3 times for the average VDV. This study was conducted to improve the weaknesses in the past studies, namely the selection the right tri-axial piezoelectric accelerometer which is used exclusively for recording WBV exposure readings, the selection of two types of road surfaces, number of tested truck and variable vehicle speeds. Major contributions newly made in this study is that the developed model is more reliable with the tested truck number is four and test has been performed on two different types of road surfaces.

2. Statistical analysis using Integrated Kurtosis-Based Algorithm for Z-Notch Filter Technique 3D (I-kaz 3D)

Statistical parameters, such as root mean square (RMS), kurtosis, crest factor, skewness, peak value, and signal-to-noise ratio (SNR), are widely used to detect defects. While these indicators are easy to implement, the complexity of the mechanisms involved may give rise to serious errors in interpretation (Jena and Panigrahi, 2013). For this study, the investigation of statistical parameters derived from WBV exposure time domain signals is performed using I-kaz 3D. The I-kaz™ method was developed by Nuawi et al. (2008a) based on the concept of data scattering about the data centroid and classification of the display based on inferential statistics. It is used to model data patterns that account for randomness and draw