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Evaluation of whole-body vibration exposure experienced by operators of a compact wheel loader according to ISO 2631-1:1997 and ISO 2631-5:2004

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ABSTRACT

Limited studies were carried out to evaluate the whole-body vibration (WBV) exposure experienced by operators of compact wheel loaders (CWLs) according to ISO 2631-1:1997. No study was carried out according to ISO 2631-5:2004. Therefore, evaluation of the WBV exposure using these two standards was carried out and the results were compared in this study. Tri-axial accelerations were measured at the seat/operator interface on a medium-sized CWL. The vibration measurements were carried out in ten different operations, such as the V-cycle and the driving over different road surfaces. In order to represent the daily work of the CWL, seven scenarios were proposed. These scenarios are comprised of V-cycle and driving over different distances. The evaluation result according to ISO 2631-1:1997 showed that the permitted daily exposure durations of six scenarios estimated using the vibration dose value (VDV) method did not exceed 8 h. For the pure V-cycle and the combination of V-cycle and slow driving, the permitted daily exposure durations estimated according to ISO 2631-1:1997 were shorter than those estimated according to ISO 2631-5:2004. However, for the combination of V-cycle and fast driving, the permitted daily exposure durations estimated according to ISO 2631-1:1997 were longer than those estimated according to ISO 2631-5:2004.

Relevance to industry: This study evaluated the effect of WBV arising from a CWL on human health according to ISO 2631-1:1997 and ISO 2631-5:2004. Evaluation results show that boundaries of the health guidance caution zone in ISO 2631-5:2004 are higher than those in ISO 2631-1:1997.

1. Introduction

Workplaces with high level of whole-body vibration (WBV) are numerous and mainly include the driver seats on agricultural tractors, construction machines and transportation vehicles (Smith and Leggat, 2005). The long-term exposure to the WBV has adverse effects on the human health. It causes a series of health problems especially in the back area, such as spine degeneration and spinal disc disease (Bovenzi and Hulshof, 1999; Hulshof and van Zanten, 1987). The symptom low back pain (LBP) is more prevalent in the workers exposed to vibration than in those who are not (Boshuizen et al., 1990; Bovenzi and Betta, 1994; Bovenzi et al., 2006; Lings and Leboeuf-Yde, 2000).

The International Organization for Standardization (ISO) published the standard ISO 2631-1:1997 to evaluate the effect of periodic, random and transient WBV on the human health. According to this standard, many studies evaluated the WBV exposure on different types of vehicles, including agricultural tractors (Futatsuka et al., 1998; Paddan and Griffin, 2002), construction machines (Aye, 2009; Cann et al., 2003; Coggins et al., 2010) and transportation vehicles (Coggins et al., 2010; Paddan and Griffin, 2002). In 2004, part 5 of ISO 2631 (ISO 2631-5:2004) was published, in which a new health hazard assessment method was introduced. This method was developed in a research program conducted by the U.S. Army Aeromedical Research Laboratory (USAARL) (Alem, 2005). The ISO 2631-5:2004 is used to evaluate the effect of WBV containing multiple shocks on the human health.

After the publication of ISO 2631-5:2004, both ISO 2631-1:1997 and ISO 2631-5:2004 were used in research works to predict the health risks simultaneously (Alem, 2005; Cooperrider and Gordon, 2006; Eger et al., 2008; He, 2009; Smets et al., 2010). In these

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studies, different health risks were predicted according to these two ISO standards. This caused the discussion about the health guidance caution zones (HGCZs) in these two standards. Alem (2005) and He (2009) predicted lower health risks according to ISO 2631-1:1997. Alem (2005) suggested that the HGCZ in ISO 2631-1:1997 should be lowered. Higher health risks were predicted according to ISO 2631-1:1997 in the studies of Cooperrider and Gordon (2006), Eger et al. (2008) and Smets et al. (2010). Eger et al. (2008) suggested that the HGCZ in ISO 2631-5:2004 should be lowered.

Compact wheel loaders (CWLs) are a subclass of wheel loaders that typically have engine power less than 90 kW and operating weight less than 10,000 kg. Bucket capacity and breakout force of CWLs can reach 2.5 m^3 and 77 kN respectively. Bigger wheel loaders have engine power ranging from 90 kW to 1100 kW and operating weight ranging from 10,000 kg to 200,000 kg. Their bucket capacity varies between 1.5 m^3 and 36 m^3, and their breakout force is in the range from 50 kN to 1000 kN. (Caterpillar Products; John Deere Construction Equipment; Volvo Construction Equipment).

Large effort has been made to investigate the WBV exposure on bigger wheel loaders. For example, WBV exposure on wheel loaders with operating weight ranging from 11,500 kg to 99,275 kg was estimated in studies of Aye (2009), Johanning (2011) and Tiemessen et al. (2008). Newell et al. (2005) measured the WBV on ten wheel loaders with operating weight ranging from 22,590 kg to 46,454 kg. These WBV measurements were used to study the variation in WBV on wheel loaders caused by work cycles. In the study of Blood et al. (2012), WBV measurements were conducted on a wheel loader with operating weight of 23,698 kg in three work tasks. In each work task the WBV was measured with three different tire configurations: (1) stock rubber tires, (2) rubber tires with ladder chains, and (3) rubber tires with basket chains. Effects of tire configurations and work tasks on the WBV exposure on the wheel loader were studied.

A few studies developed methods on the basis of multi-body simulation to reduce the WBV on bigger wheel loaders (Bös, 2013, 2014; Rehnberg and Drugge, 2008). Bös introduced an automatic simulation process, which was developed based on a full-vehicle model of a wheel loader (Bös, 2013, 2014). With this automatic simulation process, axle and cab suspensions on the wheel loader can be optimized for more riding comfort and operational safety. With the help of multi-body models of a wheel loader with suspended axles or unsuspended axles, Rehnberg and Drugge (2008) investigated that WBV in the vertical and the longitudinal directions on the wheel loader was reduced greatly by suspended axles.

Due to the relatively small size but still ample lift capacity and manoeuvrability, CWLs have a large market around the world, especially in North America and Europe (Ritchiewiki, 2009). However, only a few studies evaluated the WBV exposure on CWLs (Mansfield et al., 2009; Notini and Mansfield, 2004; Zhao et al., 2013). In studies of Mansfield et al. (2009) and Notini and Mansfield (2004), vibration dose values (VDVs) of the WBV on CWLs in short durations were presented. No prediction of health risks was conducted in these two studies. Zhao et al. (2013) evaluated the effect of short-term exposure to the WBV arising from a CWL on the riding comfort. The evaluation in these three studies was carried out according to ISO 2631-1:1997. Backhoe loaders are similar to CWLs in terms of operating weight and lifting capacity. In the study of Scarlett and Stayner (2005) WBV exposure on a backhoe loader was evaluated according to ISO 2631-1:1997. In the study of Langer et al. (2012) WBV was measured on two backhoe loaders before and after the operators got an education on eco-driving and vibration avoidance. The education was proven to reduce the WBV on backhoe loaders efficiently.

From the review of research works in the paragraphs above, three conclusions are obtained as follows:

1) Procedures in ISO 2631-1:1997 and ISO 2631-5:2004 lead to different prediction results of health risks caused by the WBV;
2) Only a few studies were carried out to evaluate the WBV exposure on CWLs according to ISO 2631-1:1997;
3) No study evaluates the effect of WBV arising from CWLs on the human health according to ISO 2631-5:2004.

Therefore, more studies are needed to evaluate the effect of WBV arising from CWLs according to ISO 2631-1:1997 and ISO 2631-5:2004 and to analyse the evaluation results obtained using these two standards. The objectives of this paper are listed as follows:

1) to measure the WBV at the seat/operator interface on a medium-sized CWL during its various operations;
2) to evaluate the effect of WBV arising from the CWL on the human health according to ISO 2631-1:1997 and ISO 2631-5:2004;
3) to compare the evaluation results obtained according to two ISO standards;
4) to analyse the reasons for the different evaluation results.

2. Methods

2.1. Vehicle and operator in the field tests

Field tests of vibration measurement were carried out on a medium-sized CWL in accordance with the requirement in ISO 2631-1:1997 and EN 1032:2003. The CWL is not equipped with axle suspensions. Four rubber elements are used between the vehicle frame and the cab as a spring-damper system. The seat suspension in the vertical direction is comprised of a passive air spring and an inclined hydraulic shock absorber. The seat does not have any suspension in the longitudinal and the lateral directions.

Weight of the CWL is 6400 kg when the bucket is empty and about 7900 kg when the bucket is full of gravels. Basic vehicle parameters of the CWL are given in Table 1.

The operator, who participated in the field tests, is familiar with the CWL and has more than 20 years of experience in CWL operation. His weight is 80 kg, and his height is 1.75 m. The lap belt was worn in all tests for the safety purpose.

2.2. Test operations

Operations of the CWL in the field tests were determined based on the suggestions about the typical operations of CWLs in ISO/TR 25398:2006, as well as the review of studies on the field tests of WBV measurement on wheel loaders (Aye, 2009; Blood et al., 2012; Johanning, 2011; Mansfield et al., 2009; Notini and Mansfield, 2004). The test operations and the measurement durations are presented in Table 2. Operations recommended for CWLs in ISO/TR 25398:2006 include ‘carry and driving’, ‘V-cycle’ and ‘delivery driving’. The first two operations were included in the field tests in this study. Besides these two operations, WBV measurement during

Table 1
Basic vehicle parameters of the CWL used in the field tests.

Engine output	57 kW	Wheelbase	2.15 m
Breakout force	61 kN	Width over tires	1.93 m
Bucket capacity	1.2 m^3	Max. speed in the 1st gear	6.9 km/h
Tire pressure p_f/p_r[a]	3.0/2.5 bar	Max. speed in the 2nd gear	19.8 km/h

[a] p_f, pressure of front axle wheels; p_r, pressure of rear axle wheels.