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Reducing whole-body vibration through field vibration tested heavy equipment seat retrofitting

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Abstract.
BACKGROUND: Heavy mobile equipment operation exposes operators to whole-body vibration (WBV) through the seat. The decision of which seat to retrofit a machine with is usually done statically.
OBJECTIVE: To report on the third phase of a three phase project designed to intelligently retrofit seats in heavy mobile machines with the purpose of reducing machine operator WBV exposure.
METHODS: Three slag pot haulers were retrofitted with a 6801 Isringhausen seat in which the seat pan cushion was retrofitted with Skydex™ seating material. Vibration dose values (weighted for health), vibration total values (weighted for comfort) and Seat Effective Amplitude Transmissibility were determined from field measurements.
RESULTS: WBV was reduced from the first field study to below the upper boundary of the ISO 2631-1 (1997) health guidance caution zone and comfort weighted vibration total values were reduced to the second lowest discomfort rating.
CONCLUSIONS: Steel making and other similar industries have been provided with information to more efficiently retrofit existing machines.

Keywords: Whole-body vibration, operator reported comfort, seat selection, ISO 2631-1(1997)

1. Introduction

Occupational WBV exposure occurs in many types of mobile equipment [1] and many of these exposures well exceed recommended guidelines placing workers at increased injury risk. Vibration occurs along and about three translational and three rotational axes (6-DOF) and can enter the body at any point of contact with a vibrating surface [2–4]. In the seated machine operator, vibration enters at the feet/floor, seat back/back, at the hands/controls and seat pan/buttock interfaces [2–4]. WBV exposure can be uncomfortable and has been linked to back [5–7], neck and shoulder pain [8,9]. While many factors affect vibration attenuation such as tires [10], wheel suspension [11], driving speed [12,13] and terrain [13,14], most frequently WBV vibration attenuation attempts focus on the operator seat [11]. The

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seat is the primary method of vibration transmission from the chassis of the vehicle to the operator and is often mounted to the chassis using a non-permanent fixation method. This makes it relatively easy to remove the existing operator seat, and if the frequency and magnitude of the vibration at the chassis are known, it is possible to replace it with a seat better able to reduce chassis specific vibrations. Unfortunately, the decision of which seat to use in retrofitting an existing machine is more often than not accomplished by having machine operators and others try seats in show rooms. Very often the seat that feels comfortable in the show room does not attenuate vibration effectively in an operating machine. The purpose of this multiphase project was to provide integrated steel manufacturers and others with methods and information to allow them to more efficiently retrofit seats in existing mobile machines which workers report to be particularly uncomfortable to ride in, and which may be related to a number of lost time days due to ailments associated with WBV exposure.

Results from the first project phase showed that 6-DOF vibration chassis data recorded from mobile machines in the steel making industry resulted in ISO 2631-1 (1997) [3] comfort predictions ranging from Uncomfortable to Extremely Uncomfortable [15]. It was also revealed that six of eleven tested machines had tri-axial seat vibration dose values above the health guidance caution zone (HGCZ) [16]. For phase two, field vibration profiles recorded during phase one of the project were implemented on a laboratory located 6-DOF robot [17]. This allowed for a controlled testing environment to determine an optimal seat to best attenuate vibration profiles associated with steel manufacturing mobile equipment operation. At the conclusion of phase two, a seat was identified to be retrofitted in the mobile equipment type previously found to expose steel manufacturing mobile machine operators to the highest levels of WBV [15,16]. The purpose of the current paper is to report on the third project phase which was designed to assess the WBV attenuation effectiveness of the retrofitted seat under field operating conditions.

2. Methods

As was already stated, the overall project was comprised of three phases. The first involved 6-DOF chassis acceleration data recorded for five types of mobile machines from the steel making industry [15,16]. Following field data collection, six, 20 second representative field profiles were assembled from the 'worst' WBV machine for use in the second phase which was conducted in the laboratory [17]. Profiles were implemented while subjects sat on one of three heavy equipment seats (BeGe7150, Grammar MSG 95G1721, and a 6801 Isringhausen in which the seat pan cushion was retrofitted with Skydex^{TM} seating material) mounted on a 6-DOF Parallel Robotics System Corporation (PRSCO) robot. The seats selected for testing were chosen based upon consultation between the researchers, a seating manufacturer/distributer and the cooperating steel company. Three randomized trials of each combination of seat and profile were conducted using eight male and eight female inexperienced operators as well as four male experienced operators from a participating steel making company. Assessment variables included operator reported normalized (to the operator's mean response) comfort which was verbally reported by subjects following each vibration exposure according to methods reported in Dickey et al. [18]. The other assessment variables were 6-DOF Vibration Total Value (VTV) Weighted Comfort which was assessed using a 6-DOF seat pad transducer according to ISO 2631-1 standards [3] and Seat Effective Amplitude Transmissibility (SEAT) [19] using the seat pad transducer and a second 6-DOF transducer fixed to the robotic platform. Following the lab study, and based on the lab assessment variable results coupled with skilled operator preference, the Skydex^{TM} fitted Isringhausen seat was selected as the preferred seat for retrofitting. In phase three, the Isringhausen seat with Skydex installed in the seat pad was installed in three slag pot haulers. Unfortunately, due to unscheduled

Table 1
Slag pot hauler vehicle tasks and route traveled

Vehicle	Tasks	Route	Split for analysis By
Slag pot haulers (Figure 1)	Picks up and transports pots of slag, empties them by banging (skull banging), and drives unloaded to gather a new pot	Paved and unpaved roads	Pot banging and 3 minute sections of driving loaded or unloaded

Fig. 1. Slag pot hauler.

repairs and maintenance, only one of the retrofitted slag pot haulers was available on the testing days. Slag pot hauler vehicle tasks and routes traveled can be found in Table 1. The vehicle was monitored for a minimum of 60 minutes for each of three different operators. Ethics approval was obtained from the University of Guelph Research Ethics Board. Prior to study participation, each machine operator was familiarized with all of the procedures involved in the study after which they provided informed consent.

Chassis data were collected using a MEMSense 6-DOF sensor (MEMSense, SD, USA) which was housed in a rigid IP-65 rated polycarbonate casing (Hammond Manufacturing, NY, USA). The casing was mounted using rare earth magnets directly to the machine chassis such that it did not interfere with machine operation. To determine how well the new seats were attenuating vibration, a second 6-DOF transducer was used in a seat pad transducer. This transducer consisted of two ADXL320EB dual axis accelerometers (Analog Devices Inc., MA, USA) and three ADXRS150EB gyroscopes (Analog Devices Inc., MA, USA) orthogonally placed in a Delrin^{TM} plastic casing. The seat-pad transducer and associated cables weighed approximately 670 grams with a maximum thickness of 29.3 mm. Raw voltages from both transducers were collected for a minimum of one hour at a sampling frequency of 500 Hz using two Biometrics DataLOG No. P3x8USB dataloggers (Biometrics, VA, USA).

Vibration data were processed with custom Matlab^{TM} code (Mathworks Inc., MA, USA) using the Vibratools^{TM} software package (Axiom EduTech, Ljusterö, Sweden). To correspond with instrumentation limitations as well as ISO 2631-1 (1997) [3], data were band-pass filtered with lower and upper cut-off frequencies set to 0.4 Hz and 40 Hz respectively. Running root mean squared (RMS) average accelerations, peak accelerations and vibration total value (VTV) were then calculated according to ISO 2361-1 [3]. ISO 2631-1 (1997) [3] provides a means of predicting operator comfort through a set of comfort guidelines. The perceived discomfort assessments were based on comfort weighted VTV where a multiplier of 1 was applied to all three translational axes while the roll, pitch and yaw rotational axes had multipliers of 0.63 m/rad, 0.4 m/rad and 0.2 m/rad respectively. ISO 2631-1 suggests that comfort reactions for accelerations between 0.315 m/s^2 and 0.63 m/s^2 are a little uncomfortable, 0.5 m/s^2 and 1 m/s^2 are fairly uncomfortable, 0.8 m/s^2 and 1.6 m/s^2 are uncomfortable, 1.25 m/s^2 and 2.5 m/s^2 are very uncomfortable and 2 m/s^2 or greater are extremely uncomfortable. The VTV weighted for comfort was calculated for 6-DOF using an equation similar to Eq. (1) where a is the weighted acceleration, and k is the ISO 2631-1 weighting factor, however, it was expanded to include the three rotational axes (Roll, Pitch and Yaw) in addition to the three translational ones (X, Y, and Z).

$$\text{VTV} = (k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2)^{1/2} \quad (1)$$

Vibration Dose Value (VDV) was calculated for each axis as well as for 3- and 6-DOF using Eq. (2). Each pair of VDV (seat and chassis) values were used to calculate the SEAT value according to Eq. (3).

$$\text{VDV} = \left[\int_0^t a^4(t)dt\right]^{1/4} \quad (2)$$

$$\text{SEAT\%} = 100\% \times \frac{\text{VDV}_{seat}}{\text{VDV}_{chassis}} \quad (3)$$

The SEAT function was developed to provide a simple description of seat vibration attenuation [19] but it can be used to compare vibration attenuation capabilities between different seats and can thus be used to determine the best seat for specific road vibrations [20–22]. A SEAT value greater than 100% indicates that the seat is amplifying the vibration whereas a SEAT value less than 100% represents a reduction in WBV transmission.

Health risks were assessed as per ISO 2631-1 [3] using the VDV method of analysis Eq. (2) due to Crest Factors being in excess of 9. Crest Factors are quantified as the ratio between the peak acceleration and RMS acceleration values and reflect transient spikes in the vibration signal (e.g., driving on a smooth road and then hitting a pot hole). In calculating the acceleration values for health (similar to Eq. (1), for the x- and y- axes, $k = 1.4$ and for z, $k = 1$. The k value is 0.63 rad/m for roll, 0.4 rad/m for pitch and 0.2 rad/m for yaw. Health risk is established by comparing the axis with highest VDV to the following equivalent health guidance caution zone limits. As per ISO 2631-1 [3], VDV for the highest axis was converted to an eight hour equivalent where t_n is the number of minutes in eight hours and $t_{Measured}$ is the time in minutes over which the VDV was calculated:

$$\text{VDV}_{8\ Hour\ Equivalent} = \left[\frac{t_n}{t_{Measured}} * \text{VDV}^4\right]^{1/4} \quad (4)$$

If the VDV is below 8.5 m/s$^{1.75}$, no major health effects are anticipated. If it is between 8.5 and 17 m/s$^{1.75}$, this is a zone of caution with respect to health indicating that interventions are required. If it is above 17 m/s$^{1.75}$, workers should not be exposed to this level of vibration.

A seating questionnaire was given to operators while the vibration monitoring equipment was being installed in the machine cab. The purpose of the questionnaire was to provide the participating workers with a means to inform the research team about how they felt about the new seat.

3. Results

Results from the field and the laboratory studies have been reported previously [15–17]. For the current phase, the vibration results are presented in Table 2 while the Seating Questionnaire results are contained in Table 3.

Table 2
Vibration variables (Mean ± SD across three machine operators and 29, approximately three minute data sections for one slag pot hauler)

Variable	Mean ± SD	Minimum Value	Maximum Value
$VTV_{Seat\ Comfort}$ 3-Translational Axes (m/s^2)	0.648 ± 0.118	0.285	0.867
$VTV_{Seat\ Comfort}$ 6-DOF (m/s^2)	0.704 ± 0.124	0.356	0.956
$VDV_{Seat\ Heath}$ ($m/s^{1.75}$) – Observed in Z-axis*	2.862 ± 0.643	1.867	4.652
$VDV_{Seat\ Health}$ 3-Translational Axes ($m/s^{1.75}$)*	3.563 ± 0.777	2.588	5.807
$VDV_{Seat\ Health}$ 6-DOF ($m/s^{1.75}$)*	3.972 ± 0.865	2.685	5.948
$VDV_{Seat\ Health-8\ Hour\ Equivalent}$ Z-axis ($m/s^{1.75}$)	10.179 ± 2.287	6.640	16.545
SEAT-3 Translational Axes (%)	96.12 ± 10.34	72.30	116.97
SEAT-6-DOF (%)	106.34 ± 11.20	83.15	129.35

*Calculated over approximately three minutes.

Table 3
Seating Questionnaire results ($n = 3$ machine operators)

Question	Operator Response
In general do you find the seat comfortable?	3/3-Yes
Does the seat pan (what you sit on) provide you with enough support?	3/3-Yes;
Do you think the seat pan is too long, too short or OK?	3/3-OK
Do you think the seat pan is too wide, too narrow or OK?	3/3-OK
Do you think the back rest has enough support for the lower back?	2-Yes;1-No
Do you think the backrest is too low, too high or OK?	3/3-OK
Do you think the backrest is too wide, too narrow or OK?	3/3-OK
Do you adjust your seat before you begin to operate the machine?	3/3-Yes
Have you ever been given instructions on how to adjust your seat?	1-Yes; 2-No
Do any of the seat features interfere with comfortably wearing your seatbelt?	3/3-No
Would you change anything to make your seat more comfortable?	*1-Yes; 2-No

*Operator who answered 'Yes' indicated that they would like to have their own seat cover.

The VTV values weighted for comfort suggested that for both the translational and combined translational and rotational axes, the ride would be fairly uncomfortable according to ISO-2631-1 which is the second lowest level of discomfort (0.5 m/s^2 to 1 m/s^2) (Table 2). The highest VDV health weighted value was observed in the Z (vertical axis) (Table 2). For this axis, the $VDV_{8\ Hour\ Equivalent}$ exposed operators to the middle health risk category indicating that interventions were still needed (i.e., it was between 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$). The SEAT values for the translational axes showed that the seat was attenuating the vibration slightly whereas in the 6-DOF case, the vibration was being amplified slightly (Table 2). The seating questionnaire results were all positive with the exceptions that one operator would have like to have more support for the lower back and another operator would like to have their own seat cover (Table 3).

4. Discussion

Results from phase one of the project revealed elevated chassis and seat vibration levels for five mobile machine types used in the steel making industry. Using field-based vibration profiles, the robot-based laboratory testing successfully informed the cooperating steel company the best of three potential seats for retrofitting their machines.

In our phase one field data collection, VTV values for slag pot haulers ranged between 1.7–2.6 m/s^2 [15,16] whereas in the current work, the slag pot hauler with the new seat installed ranged between a minimum of 0.356 and a maximum of 0.956 m/s^2 which was an improvement. The slag pot hauler comfort levels from our previous field study placed in the top two categories of discomfort (Very Uncomfortable and Extremely Uncomfortable) [15,16] whereas the slag pot hauler with the new seat installed placed in the second lowest discomfort rating (Fairly Uncomfortable).

During the post-seat retrofitting field testing phase (phase three), the $VDV_{8\ Hour\ Equivalent}$ levels at the seat ranged between 6.640 and 16.545 m/s$^{1.75}$ exposing operators to the middle health risk category indicating that interventions were still required. As per ISO-2631-1 (1997) [3], health effects were established by comparing the axis with highest VDV to the equivalent health guidance caution zone limits. The obtained values were nonetheless an improvement over data obtained during our first field study involving slag pot haulers where the Z-axis VDV (which was the axis where the highest VDV value was obtained) ranged from 11 to approximately 25 m/s$^{1.75}$ placing the machines in the top two health risk categories [16].

The SEAT values for the translational axes show that the seat was attenuating the vibration slightly whereas in the 6-DOF case, the vibration was being amplified slightly. Unfortunately we did not collect 6-DOF acceleration data from the seat in phase one field testing so we do not have comparative data. However, it is not uncommon for seats to amplify vibration [1,22,23]. As an example, Cation et al. [1] found that skidder seats amplified vibration almost 200% for some axes. In their comprehensive study of 100 seat models installed in 14 different vehicle types, Paddan and Griffin [22] observed SEAT values which ranged from 47.0–118.7%. Even more interesting is that their suggestion that 94% of the vehicles might benefit from interchanging some of the seats. Nonetheless, when the SEAT results from the current project are considered coupled with the VTV comfort weighted results (i.e., fairly uncomfortable) and the $VDV_{Seat\ Health-8\ Hour\ Equivalent}$ values, it underscores the point that perhaps seating technology is not where it needs to be. Seating designers should still be striving to improve vibration attenuation in their heavy equipment seats.

The results obtained from the questionnaire were generally positive indicating that the operators were happy with the new seat. Overall, the new seat performed well as evidenced by the lower predicted health risk and improved comfort levels over our initial field testing. Prior to seat installation, the participating company had a change in management and the timeline for full seat implementation was extended, therefore, only three vehicles had been retrofitted with the new seat at the time of testing. Additionally, two of the three pot haulers were unavailable for testing due to unscheduled maintenance and repairs. At the time of writing of this paper, an additional 12 machines have been retrofitted with the Skydex^{TM} modified 6801 Isringhausen air suspension seat. Given the 24/7 slag pot hauler machine operation, each seat lasts approximately one year prior to needing replacement. The research team conducted multiple trials from one machine using three different operators over a three day period. The intention was to measure many more machines and a second machine type (heavy lift transporter), however, the data that were collected confirmed the results of the lab testing. The other benefits that occurred as a result of phase one field testing recommendations were improved road maintenance resulting in an increased number of paved roads, an improved pot liming method which resulted in fewer skull bangs leading to reduced pitch (which was what the operators indicated was their biggest concern) and reduced speed limits. Improved road maintenance and reduced driving speeds are well known to result in decreased exposure to WBV [24], therefore, resulting decreases in WBV exposure cannot be attributed to the retrofitted seat alone. These improved workplace changes could have resulted in reduced vibration exposure so we are not able to definitely say that the reductions in WBV exposure were due solely to the new seat. Unfortunately, this is but one of the many challenges of field based research. This does not minimize the importance of the findings, however, it does underscore the importance of conducting the full spectrum of field to laboratory to field study which was the overarching purpose of the three phases of this project. The final phase of the project suggests that the selected seat improved overall vibration exposure and improved comfort.

5. Conclusions

The three phases of this project have provided the steel making and other similar industries with information which will allow them to more efficiently retrofit existing machines which workers report to be particularly uncomfortable to ride in, and which may be related to a substantial number of lost time days due to ailments associated with WBV exposure. Perhaps more important, however, is that the project highlights that the practice of having operators try seats in show rooms in order to choose a seat for retrofitting mobile equipment is an extremely poor and potentially expensive seat retrofitting method. More often than not, a seat that is found to be comfortable in a showroom does not do an effective job attenuating vibration after it is installed in a machine. However, it is recognized that most companies cannot go to the trouble of measuring vibration levels, creating profiles and running them on a 6-DOF robotic simulator to choose the most appropriate seat for retrofitting. However, given that industrial mobile equipment is quite costly, companies can and should require industrial seat suppliers and machine manufacturers to understand company requirements by potentially going into the field and measuring vibration levels in the environments that the seats will be used in. In the case of this project, the research team worked very closely with a heavy equipment seating manufacturer/distributor to provide guidance on the commercially available seats that were evaluated in Phase two of the study.

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Conflict of interest

The authors have no conflict of interest to report.

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