Original scientific paper

# Vibration Exposure in Forwarder Work: Effects of Work Element and Grapple Type

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***Abstract***

*Exposure to whole body vibration (*WBV*) is a major concern in mechanized forestry work because its adverse effects may become exacerbated by repetitive hand and arm movements, and non-neutral body postures. Moreover, shock-type vibrations have recently been suggested as a possible agent behind pains in the neck and shoulders of forest machine operators. Shocks have been identified in forwarders during loading, but the effects of crane work in forwarders have, to the best of our knowledge, not been studied. Thus, the aim of this study was to assess contributions of crane work elements, and potential effects of the use of three grapple and brake-link combinations, to vibration exposure levels in a small forwarder. Repeated measurements of cabin* WBV *were acquired, and work elements timed, as a single experienced operator forwarded wood piles on a standardized track in northern Sweden, using the same forwarder and work procedures with each grapple and brake-link combination. The studied crane equipment was found to have little or no effect on the daily* WBV *exposure. Furthermore, exposure to shock-type vibrations while loading appears to be due to driving rather than crane work. However, there were fewer collisions with remaining trees while using the tilt grapple with brake link, suggesting its use provides a more relaxed and comfortable work environment for forwarder operators and financial benefits for the forest owner by reducing damage in the remaining stand.*

*Keywords: crane work, forestry, forest machine, seated health, whole body vibration, work elements, work environment*

## 1. Introduction

Whole body vibration (*WBV*) is related to numerous health problems, inter alia various musculoskeletal, digestive and reproductive disorders, low back pain (Seidel and Heide 1986, Bovenzi and Hulshof 1999, Punnett and Wegman 2004, Burström et al. 2014), and more instant effects including motion sickness, sight impairment and fatigue (ISO 1997). In addition to health effects, *WBV* has been shown to impair performance (Conway et al. 2006), especially in accuracy based tasks, which are typical for crane work during forestry operations. It is important to restrict vibration exposure and monitor its effects on those exposed since a dose response relationship is yet to be established (Pope et al. 2002). Thus, for instance, EU Directive 2002/44/EC restricts daily exposure normalised to an eight-hour reference period, designated A(8), to 1.15 $m/s^2$ or a fourth power vibration dose value (*VDV*) of 21 $m/s^{1.75}$, and stipulates that measures should be taken to reduce the impact of *WBV* if the A(8) value exceeds 0.5 $m/s^2$ or *VDV* exceeds 9.1 $m/s^{1.75}$. A more general guideline is to always minimize occupational vibration exposure (Burström et al. 2014).

*WBV* is a major concern in mechanized forestry work since its adverse effects are exacerbated by repetitive hand and arm movements, non-neutral body postures, and manual lifting (Punnett and Wegman 2004, Okunribido et al. 2006, Lis et al. 2007, Burström et al. 2014). Operators of forest machines have a high prevalence of musculoskeletal symptoms in the lower back, neck and shoulders (Rehn et al. 2002, Jack and Oliver 2008), which may be at least partly linked to their *WBV* exposure, although the association between *WBV* exposure and neck and arm pain has not been clearly established (Rehn et al. 2009). However, it is suggested that the high prevalence of neck pain among forest machine operators is associated with exposure to shock-type vibration (Rehn et al. 2009). However, shocks may also be more important than sinusoidal vibration with regards to low back pains (Okunribido et al. 2006). Hence, reducing *WBV* should improve the work environment in forestry. Furthermore, reducing vibrations may also reduce machine wear and damage to the ground (Rieppo et al. 2002).

Due in large part to the ergonomic problems, numerous aspects of *WBV* in forestry work have been intensively researched. These aspects include effects of dampening systems for forestry vehicles (Gellerstedt 1998, Sherwin et al. 2004, Baes 2008) and both chairs and cushioning (Boileau and Rakheja 1990, Sankar and Afonso 1993, Mansfield et al. 2002, Cation et al. 2008, Ji et al. 2015). Vibrations associated with different forest machines and machine systems have also been examined (Rehn et al. 2005b, Gerasimov and Sokolov 2009), and attempts have been made to establish dose response relationships (Rehn et al. 2009), and standardize measurement techniques (Rehn et al. 2005a, Burström et al. 2006).

During work studies, forwarding is normally divided into the work elements (*WEs*) driving (empty or loaded), loading and unloading. Vibration exposure during these *WEs* has been evaluated, driving has been identified as the major source of *WBV*, and the operator is exposed to higher vibration levels when driving empty than when driving loaded (Hansson 1990, Rehn et al. 2005a). One of few studies reporting both r.m.s and shock sensitive *VDV* values found exposure to shock-type vibrations to be common while loading, but the shocks are believed to mainly originate from simultaneous driving between piles in uneven terrain (Rehn et al. 2005a). However, to our knowledge, no previous studies have examined *WBV* exposure levels in sufficient detail to evaluate exposure during crane *WEs*.

Furthermore, most previous studies have focused on vibrations associated with large forest machines (10 to 20 tonnes), which are almost exclusively used in industrial applications. Thus, there is a lack of information on *WBV* in small forwarders (lighter than 4 tonnes), which are used by both professionals and self-employed non-industrial private forest owners (cf. Nordfjell et al. 2003, Lindroos et al. 2005). There are serious concerns about both of these groups. Professionals continuously use the machines when working (cf. Passicot and Murphy 2013), so they are highly sensitive to variations in the machine design, while the latter are occasional users who are heavily represented in accident statistics, but difficult to inform about preventive actions (Lindroos and Burström 2010). Thus, for both groups it seems highly important to identify and implement modifications that minimize vibrations.

Vibration exposure in vehicles may be affected by not only driver seats and dampening systems, but also working techniques, which are influenced by the operators' experience and equipment. For example, vibration exposure of professional taxi drivers and train operators reportedly declines as their work experience increases (Chen et al. 2003), and forwarder operators' working techniques reportedly influence *WBV* levels while driving loaded (Rehn et al. 2005a). Brake links and tilt grapples are equipment that may alter work techniques during forwarder crane work. Brake-links, placed between the crane tip and grapple (or other tool) are common equipment on large forest machines and help to increase precision by reducing swinging movements of the grapple. Standard brake-links are static, but an active brake-link that can be used to brake when desired has potential capacity to further increase the precision of movements. A tilt grapple provides not only the features of an active brake-link but also the possibility of precisely tilting the grapple and the gripped logs. The use of tilt grapples has been found to increase productivity in forwarding, as well as reducing damage to stands (Fogdestam 2010, Nilsson 2013), but there have been no detailed studies on their effects on vibrations.

Thus, there are gaps of information on *WBV* exposure in small forwarders, the variation between *WEs* and the effect of crane equipment. Therefore, the aim of this study was to assess contributions of specific crane *WEs* to the overall vibration exposure in small forwarders and possible effects of three grapple and brake-link combinations on the *WBV* exposure.

## 2. Material and Methods

### 2.1 Experimental design

Repeated field measurements of cabin *WBV* in a forwarder were acquired, while a single operator was forwarding standardized wood piles on a standardized track, using three types of crane equipment. Each monitored work cycle (observation) corresponded to one round on the standardized track, beginning with loading the empty bunk and ending when the last log was unloaded. Through time studies, each work cycle was split into *WEs* and *WBV* were analyzed within and over *WEs*. Thus, the design consisted of two fixed factors (Crane Equipment and *WE*) within sets of repetitions (blocks). In total there were five blocks. The three types of crane equipment were randomly assigned within blocks to minimize possibilities of order and carry-over effects confounding the results.

The field study was conducted during October 7–22, 2013, with one trial (work cycle) per day for the

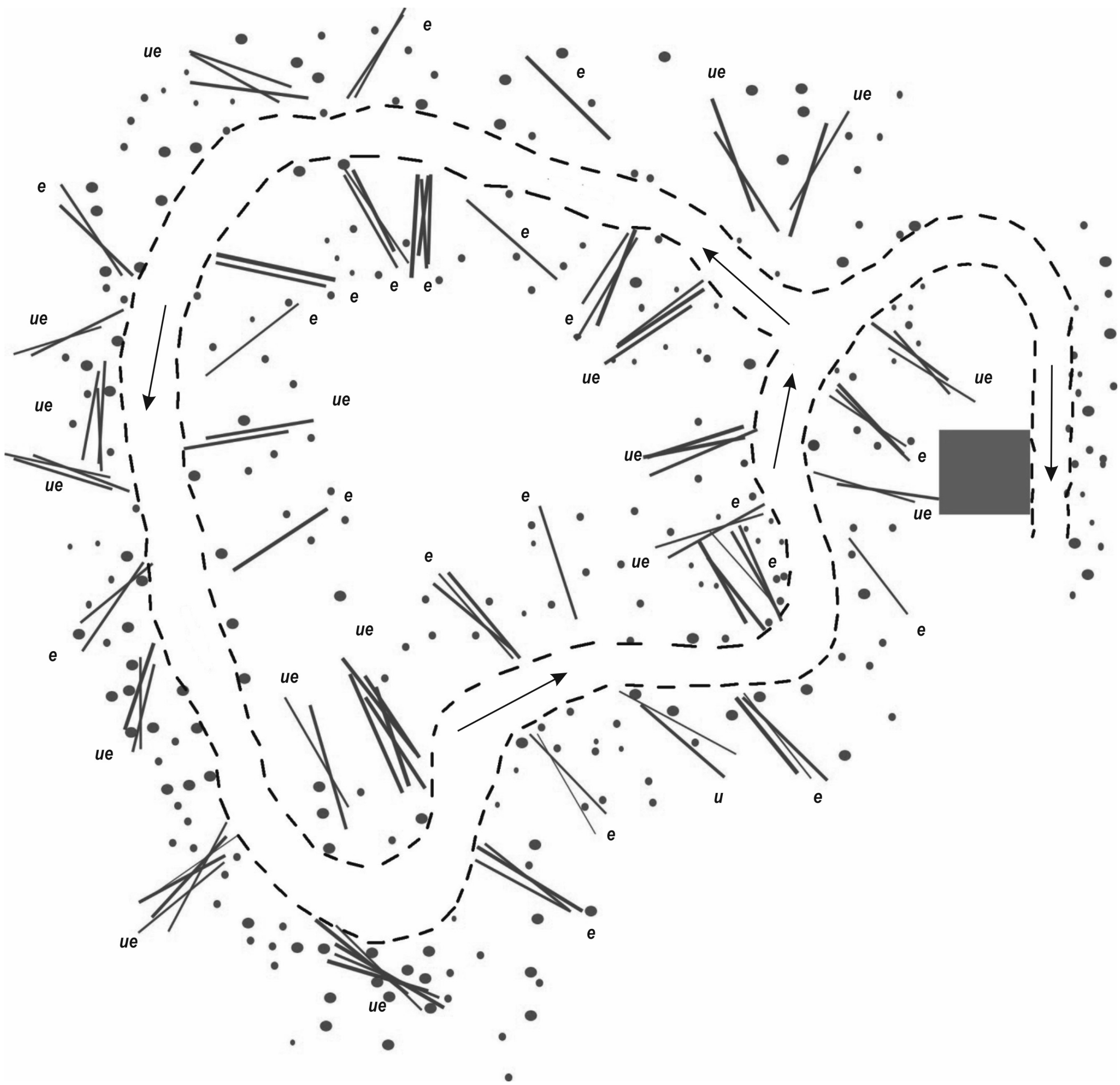

**Fig. 1** Scaled map of the 114 m long standardized track. Positions and sizes (numbers of logs) in the even (*e*) and uneven (*ue*) piles are marked by gray lines, trees in the stand by gray dots and the landing area by rectangle

first block, and subsequently two trials per day. One designated researcher filmed all the trials and made all the measurements. During the study the temperature was circa 0°C.

### 2.2 The standardized track

The study was conducted in a forest stand in the northern part of Sweden that was selected to represent a typical dense stand that had just been subjected to a first thinning (see e.g. Eriksson and Lindroos (2014) for typical Swedish conditions). The stand contained only Scots pine (*Pinus sylvestris* L.) trees, with a basal area weighted mean age of 46 years. The stand density, basal area at breast height and mean tree volume were 1370 stems per ha, 21 $m^2$/ha and 0.1 $m^3$ of solid wood over bark ($m^3$sob), respectively. The ground was extremely flat, sandy and had good carrying capacity (class 1–1–1 according to »Terrain classification for forestry work« Berg 1992). Thus, it was suitable for the tests since risks of confounding the measures of crane equipment induced vibration with vibrations due to terrain structure were minimal despite possibilities of


**Fig. 2** Vimek grapples and brake-links

simultaneous crane work and driving. The stand contained a 144 m long roughly circular track (a 2.9 m wide strip road), along which 95 pine pulpwood logs were distributed into 38 piles in a standardized manner for each trial, with a spur leading to a landing (Fig. 1). The volume of the logs was equivalent to one full load for the studied forwarder (3.3 $m^3$sob). The mean length and top diameter of the logs were 4.4 with a standard deviation (*SD*) of 0.3 and 0.078 (*SD*=0.014) m, respectively. The mean wood density, based on a sample of five logs, was 997 kg/$m^3$sob. The same logs were used, and the number, positions and sizes (i.e. numbers of logs) of the piles were kept constant during the trials. However, given logs were not always placed in given piles, thus the volumes of the piles may have varied slightly between repetitions. Each pile contained 1–5 logs, and could be handled with one grip of the grapple. The center of each pile was placed at a fixed distance between 1.5 and 5.0 m from the center of the strip road. Twenty-one piles were placed to the outer side of the circular road and slightly fewer (17) to the inner side (due to spatial limitations). The piles were always placed at the same angle with respect to the strip road. In each of the 38 piles, all butt ends were oriented in the same direction. For 20 of the piles, logs were placed so that the butt end surfaces were vertically level with each other (even piles), while for the other 18 piles their vertical positions were varied by up to 0.7–1 m (uneven piles).

During each trial, the loading started at the beginning of the track (so there was no driving empty), and the last 36 m of the track was driven with a full load (so there was 108 m of driving while loading). At the landing, logs were unloaded onto a pre-marked area for roadside-piles.

### 2.3 Base machine and crane equipment

A standard 3.5 tonnes Vimek 608.2 BioCombi forwarder was used in the study (Vimek AB, Vindeln, Sweden). The forwarder was equipped with a standard crane with a reach of 5.2 m and a lifting torque of about 20 kNm. The three studied types of crane equipment (grapple and brake-link combinations) were: a Vimek tilt grapple with a Vimek dynamic brake-link (braked tilt grapple, Fig. 2a); a Vimek standard grapple with Vimek dynamic brake-link (brake-link grapple, Fig. 2b); and a Vimek standard grapple with no brake-link (standard grapple, Fig. 2c). The gripping area was the same for all grapples (0.16 $m^2$). The tilting capacity of the braked tilt grapple was 1.3 kNm. The weights of the braked tilt grapple, brake-link grapple and standard grapple were 127, 101 and 81 kg, respectively. Thus, the mass of a single pile was not a limiting factor for the crane or any of the studied grapples.

### 2.4 Operator and work instructions

In order to avoid errors between subject variations (Lindroos 2010, Häggström et al. 2015), a single operator with previous experience of forestry time studies operated the forwarder throughout the study. The operator was male, 68 years old, familiar with the forwarder used in the study and had 30 years of experience in forwarding. Before the study, he had experience with all the studied types of grapples and brake-links, but little experience with the braked tilt grapple.

The operator first had a training session of one work cycle with each of the grapple and brake-link combinations, during which he was instructed to find a preferred working method for all three crane equipment types. He was then instructed to use the selected work patterns throughout the study. The end surfaces of gripped logs were to be aligned before loading only when the operator considered it necessary. When aligning end surfaces, the operator was instructed to do it against the headboard with the standard and brake-link grapples and vertically against the ground with the braked tilt grapple.

Between trials, the operator had the chance to get to know the equipment to be used in the following trial while re-arranging the logs along the track.

### 2.5 Time study

A LEGRIA HF S200 high definition video camera (Canon Inc., Tokyo, Japan) was used to record the work in each trial. ProTime Estimation software (Proplanner, Ames, USA) was then used to measure times of the seven defined, non-overlapping work elements (*WE*) described in Table 1. Collisions between the grapple or lifted logs, and trees or the base machine were also counted.

### 2.6 Vibration measurements

Vibrations were measured in three orthogonal axes according to ISO 2631-1 (ISO 1997) using a MTi-G triaxial accelerometer (Xsens, Enschede, The Netherlands) placed on the floor close to the center of the cabin, in front of the chair. The placement ensured that the operator's weight, height and the chair dampening would not affect the measures. Samples were taken at a frequency of 100 Hz during each, approximately 40 minute long, work cycle, using a XKF Scenario »2.7 Automotive unit« (Xsens, Enschede, The Netherlands). The measuring equipment was checked using a Brüel & Kjær 4294 calibrator after the measurements.

### 2.7 Data analyses

All data processing was performed offline using a commercial software package (MATLAB R2014a 8.3, The MathWorks Inc., Natick, USA) with the »Continuous Sound and Vibration Analysis« program (Zechmann 2013). The acceleration data were converted from the recorded time domain to frequency domain with a frequency range up to 50 Hz, i.e. the maximum frequency range that can be calculated from 100 Hz output. In the analyses, 1/3 octave band values were calculated from 0.1 to 50 Hz. The resulting data were then used to calculate frequency weighted r.m.s. acceleration and *VDV* values with respect to health effects on a seated driver in accordance with ISO 2631-1

**Table 1** Definitions of time study work elements

| Work element | Definition | Priority |
|---|---|---|
| Crane out[1] | Begins when the crane starts moving towards a pile on the ground and stops when grip begins | 1 |
| Grip[1] | Begins when the grapple is placed against the pile and stops when all logs are gripped and crane in begins | 1 |
| Crane in[1] | Begins when the grapple is loaded and the crane starts moving towards the bunk and stops with release | 1 |
| Release & reorganise[1] | The sum of release (which begins when the grapple is inside the supports above the bunk and ends when no log has contact with the grapple) and reorganise (the time the operator spends reorganizing logs on the bunk) | 1 |
| Unloading[1] | Begins when the crane starts moving for unloading on the roadside landing and stops when all logs are unloaded | 1 |
| Driving | Begins when the forwarder wheels start to move without the crane being active and stops when the wheels stop or crane movements are initiated, whichever comes first | 2 |
| Other working time | All time that is not covered by any of the definitions above, including disruptions | 3 |

Note: If multiple work elements were performed simultaneously, time consumption was recorded for the work element with the highest order of priority (lowest number)
[1] The WE crane work used in the analysis includes all the crane activities pooled

**Table 2** Assumptions made during calculation of the time distribution for each work element (*WE*) during one full day (8 hours) of work with the forwarder

| Parameter | Value |
|---|---|
| Daily work hours, h | 8 |
| Technical utility[1], % | 88–100 |
| Conversion constant $PMh_{15}$ to $PMh_0$[2] | 0.9 |
| Proportion of crane work during loading[3], % | 50–90 |
| Work cycle (including driving empty), % | |
| Proportion of loading[4] | 45 |
| Proportion of unloading[4] | 15 |
| Proportion of driving empty[4] | 24 |
| Proportion of driving loaded[4] | 16 |
| Crane Activity (without unloading), % | |
| Proportion of Release & Reorganise[5] | 32 |
| Proportion of grip[5] | 14 |
| Proportion of crane in[5] | 34 |
| Proportion of crane out[5] | 19 |

[1] Based on Nordfjell et al. (2010)
[2] Based on unpublished material, Skogforsk
[3] Based on Manner et al. (2013)
[4] Based on Rehn et al. (2005a)
[5] Based on observed time distribution in the present study

**Table 3** Ranges of the work elements' estimated contributions (%) to the total daily *WBV* dose during the studied forwarding operations, based on the average and maximal measured $a_{wz}$ and time distributions presented in Table 2

| Type of work | Work element | Contribution, % |
|---|---|---|
| Work cycle | Crane work[1] | 33–59 |
| | Driving | 41–67 |
| Crane activity | Crane in | 7–15 |
| | Crane out | 3–6 |
| | Grip | 2–5 |
| | Release & Reorganise | 7–14 |
| | Unloading | 15–20 |

(ISO 1997). The weighted r.m.s. values were calculated with respect to all three orthogonal axes, $a_{wx}$ (back and forth), $a_{wy}$ (lateral) and $a_{wz}$ (vertical), and their sum vector ($a_v$). Similarly, *VDV* was calculated for all three orthogonal axes ($VDV_z$, $VDV_y$ and $VDV_z$) and the vector value ($VDV_v$) over each measurement period. Furthermore, crest factors were calculated for all orthogonal axes as well as the 8 hour equivalent, A(8), value over each measurement period.

### 2.8 Statistical analysis

Data were analyzed using Minitab 16 (Minitab Ltd, State College, PA, USA). Analysis of Variance (ANOVA) was used to analyze the fixed effects of *WE* and Crane Equipment type, and the fixed interaction between them, on the vibration measures. The ANOVA models also included the random block effect. A general linear model (*GLM*) was applied when analyzing the ANOVA models, and Tukey's Honest Significant Difference (*HSD*) test of means was used for pairwise comparisons.

For *WE*, two sets of treatment were analyzed. The first set (denoted Work Cycle) included two levels (crane work, i.e. the sum of all crane *WEs*, versus driving,) and the second set (denoted Crane Activity) included five levels (release & reorganize, grip, crane in, crane out and unloading,). Other working time was excluded from analyses. The same levels of Crane Equipment were used in both analyses.

In a third set of analyses, effects of Crane Equipment were analyzed using a single pooled *WE* (crane work). Alignments of end surfaces, collisions with residual trees and collisions with the machine were included as covariates to investigate the relationships between vibration measures and collisions. In a fourth set of analyses, effects of Crane Equipment type on the number of collisions, and alignments, were analyzed with a *GLM* including block as a random factor.

ANOVA assumptions of independence, homoscedasticity and normality of residuals were not sufficiently violated to require transformation of the data, according to ocular inspection of residual plots. In all analyses, the significance level was set to 5%.

## 3. Results

Each of the 15 observations (five repeated trials with each of the three equipment types) lasted about 40 minutes, providing 9 hours and 22 minutes of recordings in total. Of that time, 5% was classified as other working time with a mean duration per observation of 105 (*SD*=83) s, which was excluded from further analysis. So, the average duration of work cycles was 2122 (*SD*=152), 2077 (*SD*=101) and 2229 (*SD*=65) s, respectively, for operations with the braked tilt grapple, break-link grapple and standard grapple. Missing

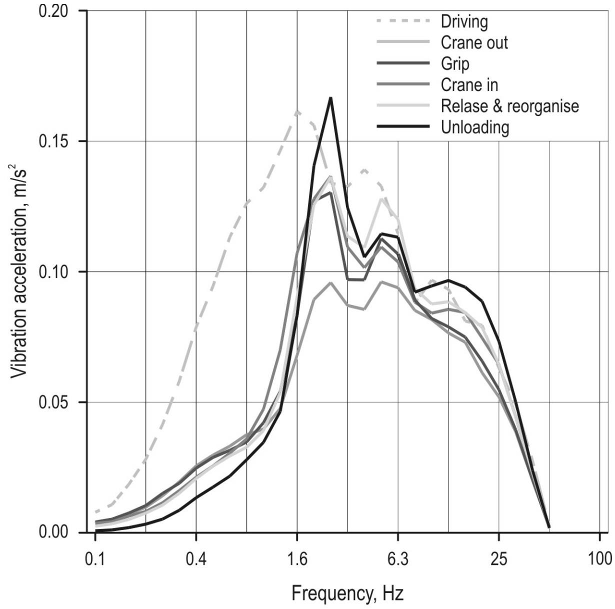


**Fig. 3** Mean values of vibrations measured at the floor of the forwarder as a function of frequency (1/3-octave bands) for each indicated work element (*WE*) during driving and crane work (means of 15 observations, i.e. pooled data for trials with all types of crane equipment)

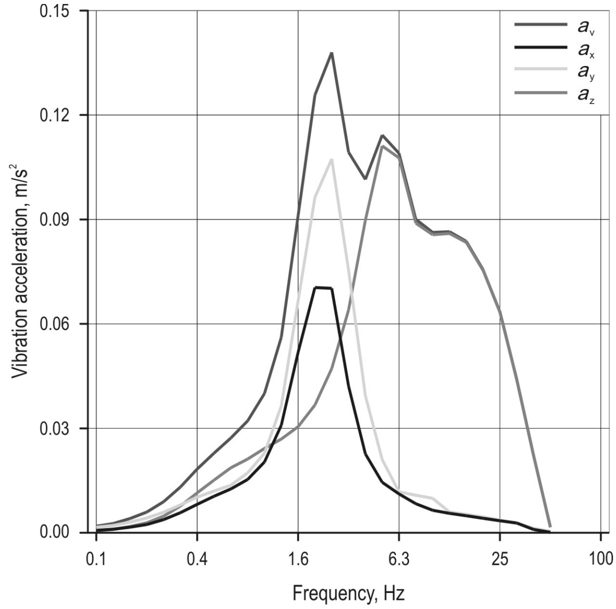


**Fig. 4** Mean values of vibrations measured at the floor of the forwarder as a function of frequency (1/3-octave bands) for the pooled crane work in all three directions ($a_x$, $a_y$, $a_z$) and the sum vector ($a_v$) (mean of 15 observations, i.e. pooled data for trials with all types of crane equipment)

data for 4, 10 and 4% of the work cycles with the respective grapples were not included in the calculation of the total time.

Based on the assumptions in Table 2, the daily total vibration exposure dose was on average 0.3 m/s$^2$ and the estimated maximum dose was 0.38 m/s$^2$. Gener-

**Table 4** Frequency weighted acceleration in the three orthogonal axes (*x*, *y* and *z*), the sum vector (*v*) and the A(8) value for indicated work elements (based on pooled data for trials with all types of crane equipment) according to »health« in ISO 2631-1. Measurements were taken at the feet

| Type of work | *WE* | *N* | Duration | $a_{wx}$ | | $a_{wy}$ | | $a_{wz}$ | | $a_v$ | | A(8) | | $VDV_v$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | s | m/s$^2$ | | | | | | | | | | m/s$^{1.75}$ | |
| | | | | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* |
| Work cycle | Crane work[1] | 15 | 1537–1887 | $0.15^{B}$ | 0.01 | $0.21^{B}$ | 0.01 | $0.32^{B}$ | 0.08 | $0.41^{B}$ | 0.06 | $0.079^{A}$ | 0.019 | $4.24^{A}$ | 0.37 |
| | Driving | 15 | 335–502 | $0.31^{A}$ | 0.03 | $0.33^{A}$ | 0.03 | $0.35^{A}$ | 0.04 | $0.57^{A}$ | 0.05 | $0.042^{B}$ | 0.003 | $4.42^{A}$ | 0.37 |
| Crane activity | Crane in | 15 | 380–638 | $0.14^{b}$ | 0.01 | $0.23^{a}$ | 0.02 | $0.32^{bc}$ | 0.08 | $0.42^{bc}$ | 0.06 | $0.042^{a}$ | 0.010 | $3.06^{a}$ | 0.37 |
| | Crane out | 15 | 262–309 | $0.11^{c}$ | 0.01 | $0.16^{c}$ | 0.02 | $0.28^{d}$ | 0.07 | $0.34^{d}$ | 0.05 | $0.028^{c}$ | 0.007 | $2.20^{b}$ | 0.35 |
| | Grip | 15 | 157–313 | $0.11^{c}$ | 0.01 | $0.22^{a}$ | 0.02 | $0.30^{cd}$ | 0.07 | $0.39^{c}$ | 0.06 | $0.026^{c}$ | 0.005 | $2.21^{b}$ | 0.29 |
| | Release & Reorganize | 15 | 343–628 | $0.17^{a}$ | 0.02 | $0.19^{b}$ | 0.01 | $0.34^{ab}$ | 0.07 | $0.43^{ab}$ | 0.05 | $0.043^{a}$ | 0.010 | $3.01^{a}$ | 0.28 |
| | Unloading | 15 | 256–345 | $0.16^{a}$ | 0.02 | $0.23^{a}$ | 0.03 | $0.34^{a}$ | 0.09 | $0.45^{a}$ | 0.08 | $0.035^{b}$ | 0.009 | $3.02^{a}$ | 0.44 |

Note: Mean values within columns and type of work with different superscript letters (*A–B* for the full work cycle and *a–d* for crane activities) are significantly different ($p<0.05$, Turkey's *HSD*). *WE* = Work Element; *SD* = Standard Deviation

[1] Crane Work includes all crane activities pooled

**Table 5** Frequency weighted acceleration in the three orthogonal axes (*x*, *y* and *z*), the sum vector (*v*) and the A(8) value for crane work with the indicated crane equipment types according to »health« in ISO 2631-1. Measurements were taken at the feet

| Crane equipment | *N* | Duration | $a_{wx}$ | | $a_{wy}$ | | $a_{wz}$ | | $a_v$ | | A(8) | | $VDV_x$ | | $VDV_y$ | | $VDV_z$ | | $VDV_v$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *s* | $10^{-2}$m/s$^2$ | | | | | | | | | | $10^{-2}$m/s$^{1,75}$ | | | | | | | |
| | | | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Standard | 5 | 1784–1887 | 14 | 1 | 20 | 2 | 32 | 8 | 41 | 7 | 8.2 | 2.2 | 171 | 15 | 241 | 32 | 301 | 56 | 424 | 54 |
| Brakelink | 5 | 1565–1781 | 15 | 1 | 21 | 1 | 33 | 9 | 42 | 6 | 7.9 | 2.1 | 189 | 16 | 242 | 24 | 313 | 50 | 441 | 22 |
| Braked tilt grapple | 5 | 1537–1846 | 15 | 1 | 21 | 1 | 31 | 8 | 41 | 6 | 7.6 | 1.6 | 178 | 23 | 222 | 8 | 286 | 50 | 406 | 27 |

ally, driving contributed somewhat more than crane work to the daily dose (Table 3).

Low-frequency vibrations were more intense during driving than during crane work (Fig. 3). However, there were no visible differences in the frequency spectra of vibrations in the vertical (*z*) direction between the crane work (Fig. 4) and driving *WEs* (data not shown). Accelerations in the horizontal directions (*x* and *y*) were highest in the frequency range 1.25–4 Hz during crane work (Fig. 4) and 0.25–5 Hz during driving. The frequency distributions for the given *WEs* were similar when using all Crane Equipment types.

There were significant main effects of Work Cycle on all vibration measures except $VDV_v$. Mean $a_v$ was significantly higher during driving than during crane work according to the variance analysis. Furthermore, vibration acceleration magnitudes (mean weighted r.m.s) in the predominant vertical *z*-direction were also highest during driving (Table 4). However, for the time weighted r.m.s. value, A(8), the relationship was reversed (Table 4). An additional set of ANOVAs showed that this relationship between $a_z$ and A(8) also held for driving versus all the Crane Activity *WEs* (data not shown). On average, more than four times as much time was spent on crane work than on driving. A high crest factor in the *x*-direction (mean 12, max 15) indicated occurrences of shocks during crane work. Nevertheless, $VDV_x$, and $VDV_y$ were higher during driving than during crane work. In contrast, $VDV_z$ was higher during crane work than during driving. Consequently, the overall vector ($VDV_v$) was not affected by *WE*.

Crane Activities significantly affected all vibration measures, but the interaction between Crane Activities and Crane Equipment was non-significant. Crane in and release & reorganize were both the most time consuming Crane Activities and the *WEs* with the highest average vector vibrations. However, they differed in that crane in had high values in the *y*-direction while release & reorganize had high values in the *x*-direction (Table 4).

No effect of Crane Equipment type on any vibration measure was found during crane work (Table 5). However, there were significant differences between Crane Equipment types in frequencies of collisions with residual trees. Fewest trees were hit when using the braked tilt grapple and most trees were hit when using the standard grapple (Fig. 5). However, applying collisions and alignments as covariates in the ANOVA did not reveal any significant relationship between collisions or alignments and vibration levels in any direction, nor for the sum vector for any of the vibration measures.

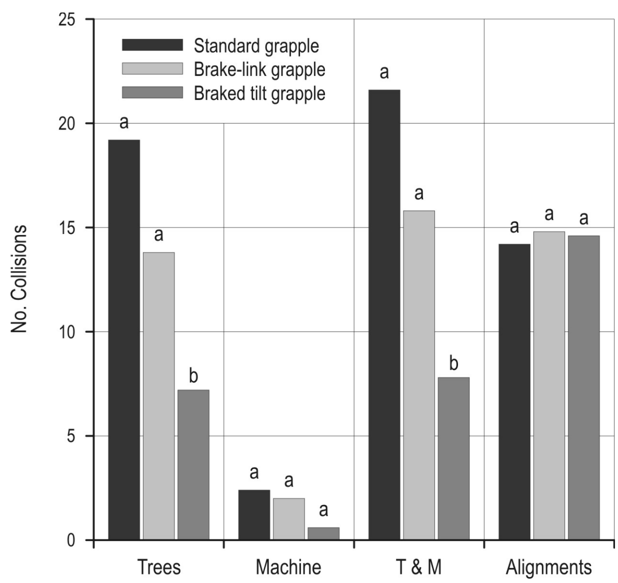


**Fig. 5** Average numbers of collisions – with residual trees (Trees), the Machine, or both (T&M) – and alignments of end surfaces of the logs per work cycle with each type of crane equipment. Means within categories with different letters are significantly different (Turkey's *HSD* $p<0.05$)

## 4. Discussion

Previous studies (Hansson 1990, Rehn et al. 2005a) have shown that the terrain significantly influences vibration levels and that *WBV* exposure is highest during driving in forwarder operations. Shock-type vibrations have also been detected during forwarder loading (cf. Rehn et al. 2005a). Nevertheless, effects of forwarder crane work have been seldom addressed, although it accounts for a high proportion of forwarding work: 50–90% of loading and unloading work time depending on extraction distance (Manner et al. 2013), and about 80% of the total monitored time in our study, reflected in higher A(8) values for crane work than for driving (Table 4). However, crane work is often done simultaneously with driving, so vibrations originating from driving confound those from crane work. Therefore, our study was conducted on a very flat, firm and even standardized track to minimize the influence of driving. Unstructured observations by the designated researcher revealed almost no occurrences of simultaneous crane and vehicle movements during the study. This indicates that our attempt to reduce driving vibrations was successful. Nevertheless, despite operating on an even track, the instantaneous vibration levels ($a_{x\text{-}z}$ and $a_v$) were still higher during driving than during any type of crane work examined in the study.

We investigated the effects of six defined crane *WEs* on *WBV*, and obtained acceleration values ranging from 0.34 to 0.45 m/s$^2$. Previous analyses of crane *WEs* during operations of a single-grip harvester have reported generally ca. 0.1 m/s$^2$ lower vibration magnitudes (measured at the cabin floor), ranging from 0.20 to 0.34 m/s$^2$, during both delimbing and felling (Burström et al. 2006). It should be noted that vibration magnitudes are normally lower at the chair, where most vibrations are transmitted to the operator. Indeed. Burström et al. (2006) found that the vibrations transmitted to the seat were lower than 0.04 m/s$^2$ (0–22% of the vibrations at the floor in the $x$, $y$ and $z$-directions). Thus, the combined *WBVs* the operator was exposed to through the seat in the studied small forwarder were probably considerably weaker than the floor-level values presented here. However, it should also be noted that chairs characteristics strongly influence vibration transmissions (Paddan and Griffin 2002), and evaluation or comparison of chairs was beyond the scope of this study.

The crane *WEs* associated with the highest vibrations in our study were associated with handling logs (i.e. crane in and release & reorganize). This implies that the weight and balance at the crane tip influenced *WBV* magnitudes. Nevertheless, despite noticeable shocks caused by impacts that were transmitted as vibrations through the crane to the cabin, no correlation was found between *WBV* exposure during the pooled crane work and grapple collisions with standing trees or the machine. Thus, these findings, in combination with the non-significant effect of crane equipment type (Table 5) and the predominance of vibrations in the $z$-direction (Table 4), imply that modifications that increase the stability of the base machine should be considered in attempts to reduce the operators' exposure to crane work induced *WBVs*. This recommendation is supported by findings that vibrations are negatively correlated with machine weight (Rehn et al. 2005a). However, other measures, for example improving hydraulics and crane control systems, may also smooth operations and reduce crane work-induced vibrations (Hansson and Servin 2010).

As mentioned above, shock-type vibration exposure is common during loading (Rehn et al. 2005a), but we found no association between either vibrations of this type or impacts during crane work. None of the *VDV* values associated with any Crane Activity were higher than the unloading values either (Table 4), which would also have indicated high frequencies of shocks during those activities (cf. Rehn et al. 2005a). Thus, it is highly likely that high *WBV* exposure while loading is due to driving between piles. Nevertheless, the differences in collision frequencies between crane equipment types observed in this study would be of interest when selecting thinning equipment to minimize damage to residual trees (Sirén et al. 2013).

An experimental setup was used, which is commonly used within forest engineering work studies (Košir et al. 2015) to enable comparison of factors of interest. However, experimental results might be difficult to generalize to other conditions. Since the smoothness of operations also affects vibration levels (Hansson and Servin 2010), these results may not be readily applied to drivers with other experience levels, grip or working technique preferences. Indeed, the rankings of crane equipment types in terms of associated vibrations may differ for other operators under the same conditions (cf. Chen et al. 2003, Purfürst and Erler 2006, Lindroos 2010). Nevertheless, the obtained results regarding crane equipment are consistent with indications of vibration effects from a previous study (Nilsson 2013) and there were no indications of differences in vibration exposure between forwarder operators during crane work (Rehn et al. 2005a). Furthermore, the variation in crane equipment types and associated differences in working techniques did not affect the *WBV* exposure during either crane work overall or the defined crane *WEs* in this study.

The upper limit of the measured frequency in this study was 100 Hz. Thus the results should be interpreted cautiously. Nevertheless, most vibration was of lower frequency than 50 Hz (Fig. 3 and Fig. 4). Thus, the limitations in measurements should not have had a major impact on the calculated exposure, and the relative levels are fully comparable. Moreover, vibrations during forwarder work depend on numerous factors and measured values are only valid under the prevailing conditions during the study. More research is hence needed to fully generalize forwarder operations with other weight, size and with other dampening systems. Nevertheless, as no significant effect of Crane Equipment was found, it is unlikely that the action value for the daily exposure would be surpassed during forwarder work due to differences in crane equipment or (crane) working technique.

## 5. Conclusions

The studied crane working techniques and crane equipment types were found to have little or no effect on the daily *WBV* exposure with respect to seated health. We found no indication that any crane *WE* or impacts from making piles should contribute significantly to shock-type vibrations assumed to be associated with neck and arm pains. Thus, the hypothesis that high levels of shock-type vibrations during loading originate from driving in an uneven terrain (cf. Rehn et al. 2005a) seems to hold. However, due to better controllability, there were fewer collisions with trees and the machine when using the braked tilt grapple. Thus its use should make the operator's work environment more relaxed and comfortable, and provide financial benefits for the land owner by reducing damage to the remaining stand.

## 6. References

Baes, J., 2008: Vibrationsdämpning av skotare. Arbetsrapport. Uppsala: Skogforsk.

Berg, S., 1992: Terrain classification system for forestry work. Kista: Forskningsstiftelsen Skogsarbeten.

Boileau, P.E., Rakheja. S., 1990: Vibration attenuation performance of suspension seats for off-road forestry vehicles. International Journal of Industrial Ergonomics 5(3): 275–291.

Bovenzi, M., Hulshof, C., 1999: An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986–1997). International Archives of Occupational and Environmental Health 72(6): 351–365.

Burström, L., Nilsson, T., Wahlström, J., 2014: Whole-body vibration and the risk of low back pain and sciatica: a systematic review and meta-analysis. International Archives of Occupational and Environmental Health 88(4): 403–418.

Burström, L., Nordfjell, T., Wästerlund, I., Tabell, L., 2006: Attempts to standardise vibration measurements in a single-grip harvester. Journal of Low Frequency Noise. Vibration and Active Control 25(1): 11–21.

Cation, S., Jack, R., Oliver, M., Dickey, J.P., Lee-Shee, N.K., 2008: Six degree of freedom whole-body vibration during forestry skidder operations. International Journal of Industrial Ergonomics 38(9–10): 739–757.

Chen, J., Chang, W., Shih, T., Chen, C., Chang, W., Dennerlein, J., Ryan, L., Christiani, D., 2003: Predictors of whole-body vibration levels among urban taxi drivers. Ergonomics 46(11): 1075–1090.

Conway, G., Szalma, J., Saxton, B., Ross, J., Hancock, P., 2006: The effects of whole-body vibration on human performance: A meta-analytic examination. Proceedings from the Human Factors and Ergonomics Society 50th Annual Meeting. October 16–20. Human Factors and Ergonomics Society: 1741–1745.

Eriksson, M., Lindroos, O., 2014: Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. International Journal of Forest Engineering 25(3): 179–200.

European Parliament and the Council of the European Union, 2002: Directive 2002/44/EC 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) 13 p.

Fogdestam, N., 2010: Studier av Biotassu Griptilt S35 i gallring. Arbetsrapport. Uppsala: Skogforsk.

Gellerstedt, S., 1998: A Self-leveling and swiveling forestry machine cab. Journal of Forest Engineering 9(1): 7–16.

Gerasimov, Y., Sokolov, A., 2009: Ergonomic characterization of harvesting work in Karelia. Croatian Journal of Forest Engineering 30(2): 159–170.

Hansson, A., Servin, M., 2010: Semi-autonomous shared control of large-scale manipulator arms. Control Engineering Practice 18(9): 1069–1076.

Hansson, J.E., 1990: Ergonomic design of large forestry machines. International Journal of Industrial Ergonomics 5(3): 255–266.

Häggström, C., Englund, M., Lindroos, O., 2015: Examining the gaze behaviors of harvester operators: an eye-tracking study. International Journal of Forest Engineering 26(2): 96–113.

International Organisation for Standardization, 1997: ISO 2631-1 Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration. Part 1: General requirements.

Jack, R.J., Oliver, M., 2008: A review of factors influencing whole-body vibration injuries in forestry mobile machine operators. International Journal of Forest Engineering 19(1): 51–65.

Ji, X., Eger, T.R., Dickey, J.P., 2015: Development of a seat selection algorithm to match industrial seats with specific forestry vibration exposures. International Journal of Forest Engineering 26(1): 48–59.

Košir, B., Magagnotti, N., Spinelli, R., 2015: The role of work studies in forest engineering: status and perspectives. International Journal of Forest Engineering 26(3): 160–170.

Lindroos, O., 2010: Scrutinizing the theory of comparative time studies with operator as a block effect. International Journal of Forest Engineering 21(1): 20–30.

Lindroos, O., Burström, L., 2010: Accident rates and types among self-employed private forest owners. Accident Analysis and Prevention 42(6): 1729–1735.

Lindroos, O., Lidestav, G., Nordfjell, T., 2005: Swedish non-industrial private forest owners: a survey of self-employment and equipment investments. Small-scale Forestry 4(4): 409–425.

Lis, A.M., Black, K.M., Korn, H., Nordin, M., 2007: Association between sitting and occupational LBP. European Spine Journal 16(2): 283–298.

Manner, J., Nordfjell, T., Lindroos, O., 2013: Effects of the number of assortments and log concentration on time consumption for forwarding. Silva Fennica 47(4): 19p.

Mansfield, N.J., Holmlund, P., Lundström, R., Nordfjell, T., Staal-Wästerlund, D., 2002: Vibration exposure in a forestry machine fitted with a saddle type suspension seat. International Journal of Vehicle Design 30(3): 223–237.

Nilsson, G., 2013: Griptiltens effekt på skotarens produktivitet. M.A. thesis. Swedish University of Agricultural Sciences, Umeå.

Nordfjell, T., Athanassiadis, D., Talbot, B., 2003: Fuel consumption in forwarders. International Journal of Forest Engineering 14(2): 11–20.

Nordfjell, T., Björheden, R., Thor, M., Wästerlund, I., 2010: Changes in technical performance, mechanical availability and prices of machines used in forest operations in Sweden from 1985 to 2010. Scandinavian Journal of Forest Research 25(4): 382–389.

Paddan, G.S., Griffin, M.J., 2002: Effect of seating on exposures to whole-body vibration in vehicles. Journal of Sound and Vibration 253(1): 215–241.

Okunribido, O.O., Magnusson, M., Pope, M.H., 2006: Low back pain in drivers: The relative role of whole-body vibration, posture and manual materials handling. Journal of Sound and Vibration 298(3): 540–555.

Passicot, P., Murphy, G., 2013: Effect of work schedule design on productivity of mechanised harvesting operations in Chile. New Zealand Journal of Forestry Science, 43(1): 1–10.

Pope, M., Magnusson, M., Lundström, R., Hulshof, C., Verbeek, J., Bovenzi, M., 2002: Guidelines for whole-body vibration health surveillance. Journal of Sound and Vibration 253(1): 131–167.

Punnett, L., Wegman, D.H., 2004: Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. Journal of Electromyography and Kinesiology 14(1): 13–23.

Purfürst, T., Erler, J., 2006: The precision of productivity models for the harvester – do we forget the human factor. In: Ackerman, P., Längin, D. & Antonides, M., eds. Precision Forestry in plantations, semi-natural and natural forests: preceedings from the IUFRO Precision Forestry Symposium, 5–10 March. South Africa, Stellenbosch University: 465–474.

Rehn, B., Bergdahl, I.A., Ahlgren, C., From, C., Järvholm, B., Lundström, R., Nilsson, T., Sundelin, G., 2002: Musculoskeletal symptoms among drivers of all-terrain vehicles. Journal of Sound and Vibration 253(1): 21–29.

Rehn, B., Lundström, R., Nilsson, L., Liljelind, I., Järvholm, B., 2005a: Variation in exposure to whole-body vibration for operators of forwarder vehicles – aspects on measurement strategies and prevention. International Journal of Industrial Ergonomics 35(9): 831–842.

Rehn, B., Nilsson, T., Lundström, R., Hagberg, M., Burström, L., 2009: Neck pain combined with arm pain among professional drivers of forest machines and the association with whole-body vibration exposure. Ergonomics 52(10): 1240–1247.

Rehn, B., Nilsson, T., Olofsson, B., Lundström, R., 2005b: Whole-body vibration exposure and non-neutral neck postures during occupational use of all-terrain vehicles. Annals of Occupational Hygiene 49(3): 267–275.

Rieppo, K., Kariniemi, A., Haarlaa, R., 2002: Possibilities to develop machinery for logging operations on sensitive forest sites. Helsinki: University of Helsinki.

Sankar, S., Afonso, M., 1993: Design and testing of lateral seat suspension for off-road vehicles. Journal of Terramechanics 30(5): 371–393.

Seidel, H., Heide. R., 1986: Long-term effects of whole-body vibration: a critical survey of the literature. International Archives of Occupational and Environmental Health 58(1): 1–26.

Sherwin, L.M., Owende, P.M.O., Kanali, C.L., Lyons, J., Ward, S.M., 2004: Influence of tyre inflation pressure on whole-body vibrations transmitted to the operator in a cut-to-length timber harvester. Applied Ergonomics 35(3): 253–261.

Sirén, M., Ala-Ilomäki, J., Mäkinen, H., Lamminen, S., Mikkola, T., 2013: Harvesting damage caused by thinning of

Norway spruce in unfrozen soil. International Journal of Forest Engineering 24(1): 60–75.

Zechmann, E., 2013: Continuous Sound and Vibration Analysis. Matlab Central File Exchange [Online]. Available: http://www.mathworks.com/matlabcentral/fileexchange/21384-continuous-sound-and-vibration-analysis [Accessed April 11 2014].

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