



THE VIBRATION EXPOSURE OF SMALL HORTICULTURAL TOOLS AND ITS REDUCTION

THESES OF DOCTORAL DISSERTATION

Helga Elvira László

Supervisors:

Dr. Zoltán Láng, CSc
Dr. Fülöp Augusztinovicz, CSc

Corvinus University of Budapest
Technical Department

Budapest
2010

PhD School

Name: Doctoral School of Horticultural Sciences

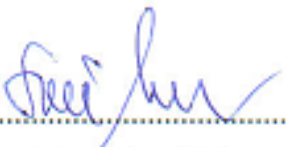
Field: Crop Sciences and Horticulture

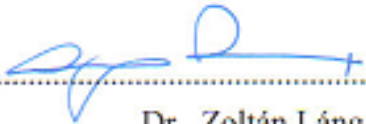
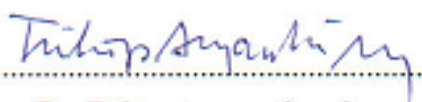
Head of Ph.D. School: Prof. Dr. Magdolna Tóth
Doctor of the Hungarian Academy of Sciences
Head of Department of Fruit Sciences
Corvinus University of Budapest,
Faculty of Horticultural Sciences

Supervisor: Dr. Zoltán Láng
Head of Technical Department, CSc
Corvinus University of Budapest,
Faculty of Horticultural Sciences
Technical Department

Dr. Fülöp Augusztinovicz
Deputy Head of Department of Telecommunications, CSc
Budapest University of Technology and Economics,
Department of Telecommunications

The applicant met the requirement of the PhD regulations of the Corvinus University of Budapest and the thesis is accepted for the defence process.


.....
Dr. Magdolna Tóth
Head of Ph.D. School


.....
Dr. Zoltán Láng

.....
Dr. Fülöp Augusztinovicz
Supervisors

1. INTRODUCTION AND AIMS OF THE STUDY

The industrial revolution and the disperse of the machines resulted a new problem: the appearance of noise and vibration. The energy transported by noise or vibration has a negative impact not only on structures or machines, but also on human health. In the last couple of decades, the interest of preventing noise induced health problems has been grown, but human vibration is still at the second place. There is very limited number of scientific publications about human vibration in Hungary.

Millions of workers in horticulture and forestry in the world, and ten thousands in Hungary might be affected by hand-arm vibration in an everyday manner (Eurofound 2005). Brush cutters, chain saws, hedge trimmers, etc typically generate this type of vibration. Due to extended use of these small hand-held machines, serious muscle-, nerve-, bone problems, collectively known as hand-arm vibration syndrome, could appear. The health problems not only affect on t he person's social interaction, but on social status through losing jobs. Moreover, the health care of these people means a huge cost for the countries.

The European Union has set up several regulations and directives related to human vibration. It has been required from the manufacturer to measure the vibration emission of the new tool before it is released, but also to measure and evaluate the hand-arm vibration (i.e. vibration exposure) during representative working conditions. The vibration emission value of a tool can be assessed either by measuring the vibration in simulate working conditions according to vibration test codes, or by estimating from a declared vibration emission value of a similar tool. The hand-arm vibration is measured and evaluated according to ISO 5349:2001 standard. On the other hand, several problems and questions have been arisen about the measurement and evaluation method of both the vibration emission of a tool and the hand-arm vibration. In many cases, the vibration emission test performed on a new machine, underestimates the vibration exposure of a used tool. Moreover, there is no scientific database that can be used to estimate the vibration emission of a new horticultural tool without measurement. Furthermore, several factor could affect on the vibration (emission and exposure) of a tool, therefore the test result is not necessarily a good indicator of the vibration exposure.

Since the hand-arm vibration is a serious health risk, the interest of its reduction has been grown. In the 1970's a new generation of machines appeared that were equipped with anti-vibration devices (Griffin 1990). Besides the new design of the machines and the technical development, the importance of personal protection equipment has been grown.

Anti-vibration glove is a personal protective equipment that minimise the health risk from hand-transmitted vibration. To be marked as an anti-vibration glove, the glove must achieve the vibration reduction criteria set out in ISO 10819:1996 standard. However, recent studies showed that several factors might influence the vibration reduction of a glove.

After I critically read the current literature, the following aims have been determined:

- Investigating the vibration exposure of some typical small horticultural machines according to ISO 5349:2001 standard in real working conditions (and comparing those with the declared vibration emission values).
- Determining some factors that could affect on the vibration emission of a tool therefore might influence the vibration exposure.
- Investigating the effect of factors not described in the ISO 5349:2001 standard that could alter the reliability of the test result.
- Investigating the effect of synthesised horticultural tool spectra on the effectiveness of anti-vibration gloves according to ISO 10819:1996 standard.
- Define and examine factors that might influence the vibration reduction performance of anti-vibration gloves.
- Based on the results, preparing some suggestions for the revision of ISO 5349:2001 and ISO 10819:1996 standards.

2. HYPOTHESES

The hypotheses of the study were the following:

- The total usage time of a horticultural tool would affect on the vibration exposure of the user; the greater the total usage time, the higher the vibration exposure.
- The holding position of a tool has a significant effect on the vibration exposure.
- The vibration reduction performance of an anti-vibration glove is significantly overestimated when it is tested with the synthesised spectra of horticultural tools.
- An anti-vibration glove shows non-linear behaviour when either the vibration magnitude or the push force applied on the handle is changed.
- Depending on the chosen subjects, the vibration exposure test or the anti-vibration test results would significantly alter.
- There is a relationship between the hand size and the vibration transmissibility of an anti-vibration glove; the greater the hand size, the weaker the glove performance.

3. MATERIALS AND METHODS

Investigation of the vibration exposure of small horticultural tools

1. Experimental design

The vibration exposure tests were performed on 18 widely used horticultural hand-held machines:

- 11 petrol engine brush cutter,
- 4 petrol engine lawn mower and
- 2 electric-, 1 petrol engine hedge trimmer.

Table 1. summarises the experimental apparatus.

Table 1. The experimental apparatus of the vibration exposure measurements.

Svantek SV 3023M tri-axial piezoelectric accelerometer
Svantek SV 50 hand-arm vibration measurement set
Svantek Svan 912AE sound & vibration analyzer
Svantek SV 06A four channels vibration measurement module
Svantek Svan 958 four channels sound and vibration analyser
Brüel & Kjær 4291 vibration calibration unit
Brüel & Kjær 4294 vibration calibration unit

The hand-transmitted vibration exposure assessment was performed according to ISO 5349:2001 standard. The acceleration signals along the x , y and z directions were recorded simultaneously. The measurements were carried out on both (i.e. left and right) handles. The vibration exposure was evaluated in two conditions: idling and cutting (with maximum engine speed). For brush cutters, tool was attached to the harness, line head was not moving for idling mode. For lawn movers, the tools were not moving or cutting during idling and cutting less than 10 cm tall grass during cutting operational mode. In case of hedge trimmers, the petrol engine version was held in the hand, but not cutting during idling. Since the electric version had no engine speed variation option, the vibration measurements were carried out with holding, but non-trimming (i.e. idling) and trimming operation (i.e. cutting). The measurement circumstances (i.e. temperature, wind, operators' parameters, etc.) were recorded. The vibration exposure assessments were carried out in 2005, 2006, 2007 between April and October and in 2009 from September to October at three locations: the experimental and research farms of Corvinus University of Budapest situated in Soroksár and Szigetcsép, and in different working areas of the main landscape gardener company in Budapest.

Table 2. summarises the experimental design of the vibration exposure measurements.

Table 2. The experimental design of the vibration exposure measurements.

Experimental session	Type of tool	No. of subjects	No. of repeats	Operational mode	Axis	Location	Performed measurement
1	all tools	3	2	idling and cutting	x, y, z	left and right hand	weighted acceleration
2	7 brush cutter 1 lawn mower 1 hedge trim.	3	2	idling and cutting	x, y, z	left and right hand	1/1 octave band analysis
3	5 brush cutter 2 lawn mower 2 hedge trim.	3	2	idling and cutting	x, y, z	left and right hand	1/3 octave band analysis
4	7 brush cutter 2 lawn mower 2 hedge trim.	1	2	idling and cutting	x, y, z	left and/or right hand	FFT analysis
5	1 lawn mower	3	8	idling	x, y, z	left and right hand	weighted acceleration
6	7 brush cutter	3	2	idling and cutting	x, y, z	left and right hand	weighted acceleration and 1/1 or 1/3 octave band analysis
7	1 brush cutter 1 hedge trim.	3	2	idling and cutting	x, y, z	left and right hand	weighted acceleration and 1/3 octave band analysis

In Experimental session5, the measurement durations were 10s, 20s, 30s and 1 min. In Experimental session6 six-six measurements (3 tool users*2 repeats) were performed on both handles in 2006, 2007 and 2009 once a year between May and June and September using the same serial number of machines. As a result, 252 vibration exposure measurements were recorded. In Experimental session7 the measurements were performed using three holding positions: with the cutting blade of the hedge trimmer parallel to the ground, with the cutting attachment tilted by 90° to the left and with the cutting attachment was tilted by 90° to the right. For the brush cutter, the holding positions were the following: the cutting head is parallel to the ground, the cutting head is tilted by 45° to the left and tilted by 45° to the right (i.e. simulating grass trimming at a hillside).

Based on preliminary experiment results, 20 s measurement duration was used during the vibration exposure assessments (except Experimental session5).

2. Data analyses

I completed almost 2800 vibration exposure measurements. The data analyses were performed using Svantek SvanPC program (version 2.7.18.) and Microsoft Office (version 10.0) Excel program. For the statistical analyses (mean, standard deviation, coefficient of variation, Friedman two-way analysis of variance, Wilcoxon matched-pairs signed ranks test and regression analysis), SPSS (version 16.0) statistical package was used. The chosen significance level (α) was 0.05

Investigating the vibration transmissibility of anti-vibration gloves

1. Experimental design

The measurements were performed using similar equipment and procedures to those specified in ISO 10819:1996 standard. The transmissibility measurements were carried out in the Human Factors Research Unit laboratory at University of Southampton between July and September 2008 and February to May in 2009. The experimental apparatus is summarised in Table 3.

Four gloves were examined: Glove1 was a nitrile rubber coated glove containing padding at the palm, Glove2 was a nitrile rubber coated glove containing silicone at the palm, Glove3 was a nitrile rubber coated glove containing gelfoam at the palm, Glove4 was a leather glove with air-bladder at the palm and at the fingers.

Table 3. The experimental apparatus of the vibration transmissibility measurements.

Derritron VP85 vibration exciter
Derritron 1.5 kW power amplifier
foil type strain gauges and Wheatstone-bridge box (type 3199-01; Yokogawa)
Brüel & Kjær 4374 piezoelectric accelerometer
Brüel & Kjær 4294 vibration calibrator
Brüel & Kjær 2635 charge amplifier
Kemo 0,1-10 kHz variable filter VBF 17
Hameg HM203-7 oscilloscope

According to the hypothesis and the measurement setup, the transmissibility measurements were grouped in three sessions:

1. session: *influence of synthesised tool spectra on glove transmissibility*

Nine vibration spectra were used in the experiment: the standard M and H spectra, the R spectrum (a random vibration with a flat constant bandwidth spectrum over the frequency range 5 to 1250 Hz) and six synthesised tool spectra (anti-vibration chain saw, non-antivibration chain saw, old and new brush cutter, hedge trimmer and a lawn mover). The acceleration power spectral densities on the horticulture tool handles were estimated from the one-third octave spectra (from 6,3 to 1000 Hz) previously reported in Hungary (except the chain saw ones that were taken from a study of Griffin 1998) using Matlab and *HVLab* ToolBox and are compared with the spectra of M and H, as defined in ISO 10819, and spectrum R. Spectrum R and the synthesised tool spectra were presented at frequency-weighted acceleration magnitudes of 3.0, 2.6, 17.2, 2.8, 3.3, 5.5 ms⁻² r.m.s., respectively. The tests were performed with bare hand and gloved hand. The push-, and grip force maintained at 50 N and at 30 N, respectively.

2. session: *influence of vibration magnitude on glove transmissibility*

In the first session, the R spectrum was generated at six magnitudes of vibration (0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 ms⁻² r.m.s.) with the push force maintained at 50 N. No grip force was applied on the handle. The measurements were performed with gloved hand only.

3. session: *influence of handle push force on glove transmissibility*

In this session, subjects applied six different push forces on the handle (5, 10, 20, 40, 50, and 80 N) with the R spectrum acceleration magnitude constant at 2.0 ms^{-2} r.m.s. No grip force was applied on the handle. The measurements were performed with gloved hand only.

Transmissibilities between the handle and the palm adapter were obtained with 10-s excitations. These transmissibility values are not directly comparable to the *TR* values in ISO 10819:1996 because they were not corrected by measurements with a bare hand. Frequency analysis was carried out with a resolution of 4.88 Hz and 196 degrees of freedom. The tests were repeated when the coherency between the input and output signal was less than 0.9. No repeat was examined. The circumstances (room temperature, subjects' anthropometrics etc.) were recorded and controlled.

Twelve right-handed male subjects participated in each session. The orders of presenting the gloves and the spectra were randomised. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

3. Data analyses

1250 transmissibility measurements were performed. The data analyses were completed using Matlab (version R2006a), *HVLab* ToolBox program and Microsoft Office Excel (version 10.0). For the statistical analyses (mean, standard deviation, coefficient of variation, Friedman two-way analysis of variance, Wilcoxon matched-pairs signed ranks test and Spearman rank correlation test), SPSS (version 16.0) statistical package was used. The chosen significance level (α) was 0.05

4. RESULTS AND DISCUSSION

Vibration exposure of small horticultural tools

4.1. Measured vibration exposure of tools in real working conditions

Brush cutters

The vibration exposures of the examined 11 brush cutters showed a high variation depending on the tool, operation mode or measurement location. The vibration total value varied between 1.880 and 4.469 ms^{-2} r.s.s.. Usually, greater vibration was measured at the left handle during idling, but for cutting, the vibration was greater on the right handle. The difference in acceleration between the two handles might be a result of the different engine speed. High variations among the measurement results were observed; generally, the coefficient of variation was greater than 10 %.

The vibration found to be dominant in the lower frequency range; the highest acceleration values lied between 63 and 125 Hz with 1/1 octave band analysis and 80 to 160 Hz with 1/3 octave band analysis.

Using the examined brush cutters four hours a day (in cutting mode) would not exceed the exposure action value that is 2.5 ms^{-2} .

Lawn mowers

The vibration total value of the examined lawn mowers were between 3.915 ms^{-2} r.s.s. and 10.039 ms^{-2} r.s.s.. Similar to the previous results, I found difference in vibration total values measured at the left and right handles; the highest acceleration variance was 41 % during idling. As it was expected, the cutting operation resulted a higher total vibration value compare to the idling results.

The 1/1 and 1/3 octave band analyses showed that the highest acceleration values occurred under 100 Hz, between 31,5 and 63 Hz.

Hedge trimmers

I measured the vibration exposure of two electric and one petrol engine hedge trimmer. Huge difference in vibration total value was observed between the two type of tool; the vibration of the petrol engine one lied between 2.243 ms^{-2} r.s.s. and 4.777 ms^{-2} r.s.s., but the highest vibration total value measured on the handle of the electric trimmer was 3.163 ms^{-2} r.s.s.. The operation mode changed the vibration total value; the difference in vibration exposure during idling and cutting reached 80 % with the petrol engine trimmer. Smaller differences (maximum 28 %) in vibration total values were observed at the front and back handle.

4.2. Influence of measurement duration on the vibration exposure test result

The vibration exposure measurements performed with a lawn mower (4 measurement duration, 8-8 repeats, 3 tool users) showed that the highest vibration total values were obtained with the 10 s and 60 s measurement duration. The coefficients of variations were the highest

among these two groups as well; between 7.4 % and 10.1 % with 10 s, and 6.3 % and 11.8 % with 60 s. Because of the r.m.s. calculation method, the effect of the unbalanced engine or the movement of the palm adaptor on the vibration total value have a greater weight with short measurement duration. The chance of moving the palm adaptor with the accelerometer might increase during long measurement time because of the fatigue of the hands. The 20 s and 30 s measurement duration found to be representative for the vibration total value and showed a better repeatability. Therefore, I used this measurement time during the experiments.

4.3. The vibration emission of a new tool and the vibration exposure of a used tool

It can be seen from my results that the declared vibration emission value of a new tool could differ from the vibration exposure of the same, but used tool. Generally, the vibration exposures of the tools obtained in real working conditions were higher than it was expected from their declared vibration emission. This was especially noticeable in case of the left (or back) handle. The two values were similar at the right handle. Since there are different standards for the measurements of the two values, this might be an explanation of the phenomena. Another reason could be that the vibration exposures were obtained with the used tools. It is possible that the usage time or the lack of service of the tools could increase the vibration emission of the machines.

4.4. Influence of total usage time on the vibration exposure of a tool

The previous results may indicate that the vibration total value depends on the usage time of the tool. My results showed that the vibration exposure increased with increasing the total working hours of the examined brush cutters. The difference in vibration exposure obtained in 2006 and 2009 varied between 19.5 % and 80.8 %. The Spearman rank correlation test verified the statistically significant correlation between the vibration total value of frequency weighted r.m.s. acceleration and the usage time ($r=0.922$, $p(\text{two tailed})=0.000$).

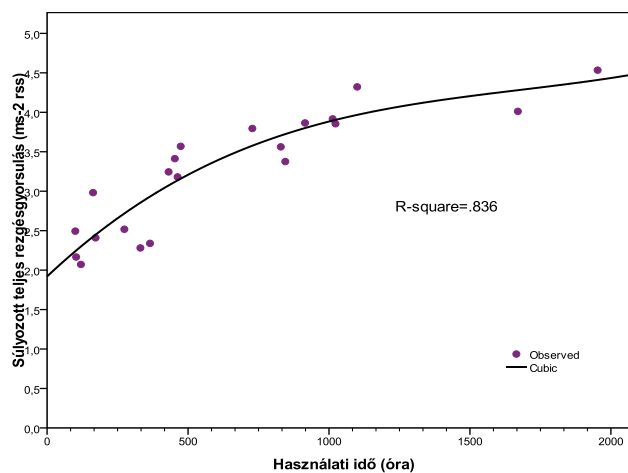


Figure 1. The result of the regression analysis that indicates a cubic relationship between the usage time and the vibration total value.

I performed regression analyses to describe the relationship between the two variables. The cubic curve found to be the best model, based on the R^2 value (Figure 1.). It can be seen from the figure, that the vibration exposure exceeded the exposure action value after around 250 hours of usage and the change in vibration total value was relatively small after 1000 hours. This indicates that the vibration exposure of the examined brush cutters might be relatively stable above this usage time.

The 1/1 and 1/3 octave band analyses showed that dominant frequency range did not change (i.e. remained in the 125-160 Hz), only the measured vibration magnitude was increased by 14.3-29.8 %.

4.5. Influence of holding position of the tool on vibration exposure

I measured the vibration exposure of a hedge trimmer and a brush cutter using three holding positions. The Friedman two-way analysis of variance test and the Wilcoxon matched-pairs signed ranks test revealed a significant difference in weighted acceleration values for each holding positions irrespective of direction of the measurement or operation modes. The weighted acceleration values were significantly higher when the hedge trimmer was tilted by 90° to the left. In contrary, the vibration exposure was significantly lower when the tool was tilted to the right, compare to the values obtained with normal holding position (except at the rear handle during cutting).

Significant differences were measured in weighted acceleration of the brush cutter, especially in the x and z directions for the front handle and all directions for the rear handle. Tilting the brush cutter to the left increased the vibration exposure, but tilting to right almost doubled the exposure. The greatest difference in vibration exposure of the normal and tilted position to the right was 2.527 ms^{-2} at the rear handle during cutting. These results suggest that the change in engine position could increase the risk of unbalance and as a result, the vibration exposure.

The Friedman and Wilcoxon statistical tests verified the statistical significant difference ($p < 0.05$) in weighted accelerations measured at the front and rear handles.

Measuring the vibration transmissibility of anti-vibration gloves

4.6. The effectiveness of anti-vibration gloves using synthesised horticultural tool spectra

Although all four gloves were labelled as anti-vibration gloves, only one glove satisfied the criteria of ISO 10819 in this experiment. For the other three gloves, the mean transmissibility value with the H spectrum exceeded the 0.6 limit.

I showed previously that the hand-held horticultural tools have a dominant vibration at the lower ($< 200 \text{ Hz}$) frequency range while the anti-vibration gloves showed considerable vibration reduction only above this frequency. As a result, the examined gloves did not show the expected vibration reduction in many cases when they were used with the horticultural tools.

Comparing the mean transmissibility values, it can be seen that the M spectrum underestimated the attenuation of the chain saw vibration, but overestimated the attenuation of the other synthesised tool spectra. In contrast, the H spectrum overestimated the attenuation of the

synthesised tool vibrations. The greatest difference in transmissibility values occurred with the H spectrum and synthesised hedge trimmer spectrum (0.559 and 0.937).

The Friedman and Wilcoxon tests verified the significant difference ($p < 0.05$) in transmissibilities obtained with the standard and synthesised horticultural tool spectra at several 1/1 octave band frequencies. The frequency response characteristics of a glove are influenced by the visco-elastic properties of the glove material and should be matched to the tool vibration spectrum.

Huge differences were observed in the individual transmissibility values. There were subjects for whom the transmissibility values exceeded the vibration reduction limit. The result indicates that depending on the selection of subjects, the overall outcome of the test could change: a glove could pass or fail the anti-vibration glove test. Furthermore the gloves are not equally effective for all users.

4.7. Influence of vibration magnitude on glove transmissibility

In theory, the vibration magnitude could modify the dynamic behaviour and hence the transfer function of the glove material. My results however showed that there were only small variations in the transmissibility values as the vibration magnitude varied (Figure 2.). The effect of vibration magnitude on glove transmissibility was statistically significant over most of the frequency range for only two gloves.

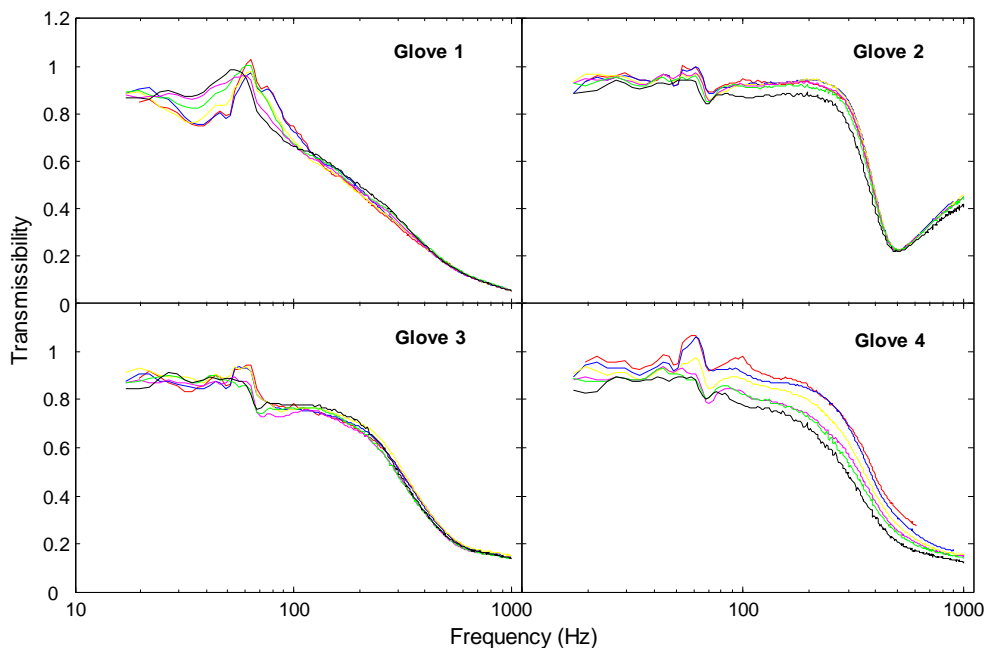


Figure 2. Effect of vibration magnitude on the transmissibility of four gloves as a function of frequency with 50-N handle push force (means for 12 subjects: — 0.25 ms^{-2} r.m.s.; — 0.5 ms^{-2} r.m.s.; — 1 ms^{-2} r.m.s.; — 2 ms^{-2} r.m.s.; — 4 ms^{-2} r.m.s.; — 8 ms^{-2} r.m.s.).

The Spearman rank correlation test showed statistically significant correlations between the magnitude of vibration and the mean TR value for three gloves, but the correlation varied in

direction ($r=0.829$, $p(\text{two tailed})=0.042$ for Glove 1; $r=-0.943$, $p(\text{two tailed})=0.005$ for Glove 2; $r=-1.00$, $p(\text{two tailed})=0.000$ for Glove 4). The transmissibility value therefore increased with increasing vibration magnitude for Glove1, but reduced with increasing vibration magnitude with Glove2 and Glove4, with no correlation between TR value and vibration magnitude for Glove3.

4.8. Influence of handle push force on glove transmissibility

My results clearly showed that with increasing push force, the transmissibility values increased (Figure 3.). With all four gloves, the transmissibility increased at all frequencies with increasing push force, with evidence of increases in the resonance frequency as the force increased (Figure 6). There were strong positive correlations between the magnitude of the applied force and the mean TR value ($r=0.943$, $p(\text{two-tailed})=0.005$ with gloves 2 and 4, and $r=1.00$, $p(\text{two-tailed})=0.000$ with gloves 1 and 3).

At all seven preferred octave centre frequencies from 16 to 1000 Hz, there were statistically significant differences in the transmissibility of the force with all four gloves ($p \leq 0.002$, Friedman).

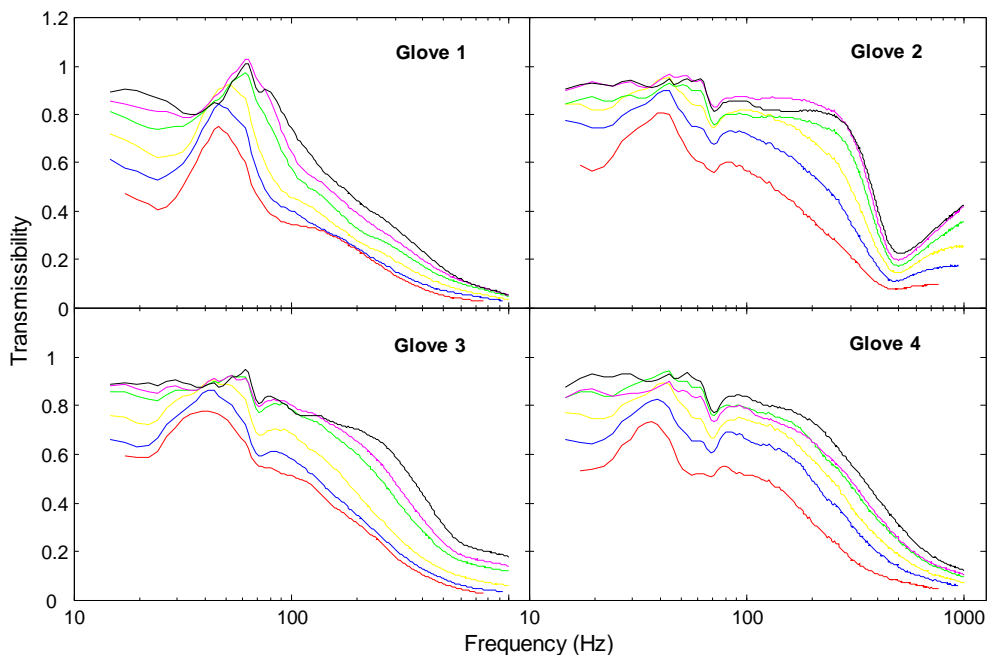


Figure 3. Effect of push force on the transmissibility of four gloves as a function of frequency with 2.0 ms^{-2} r.m.s. vibration (means for 12 subjects: — 5 N; — 10 N; — 20 N; — 40 N; — 50 N; — 80 N).

4.9. Influence of inter-subject variability on glove transmissibility

The coefficients of variation in the overall transmissibilities across the 12 subjects at each vibration magnitude and push force show the extent of inter-subject variability. The coefficients of variation for the individual transmissibility values were generally higher than 10 % especially with the synthesised tool spectra. When varying the vibration magnitude, the coefficient of

variation varied: the greater the vibration magnitude, the greater the inter-subject variability. When varying push force, the coefficient of variation seems to have decreased with increasing force.

The Spearman rank correlation test showed no significant correlation ($\alpha \leq 0.05$) between the hand size and the vibration transmissibility of the gloves.

New scientific results

Based on the four years (2005-2009) of experimental work the following scientific results were achieved:

1. I investigated the vibration exposure of three groups of horticultural tools in real working conditions. According to the results, the following conclusions were drawn:
 - a) The vibration exposure, equations (6)-(7), of the examined tools (11 brush cutters, 4 lawn movers and 1 hedge trimmer described in Chapters 4.1.1. and 5.1.1.) was dominating at the lower frequency range (100-200 Hz), where the hand-arm system shows the highest sensitivity (Aldien *et al.* 2006). This is important not only in risk assessment, but in the right choice of the vibration reduction method.
 - b) Based on the vibration exposure measurements of hedge trimmer and brush cutter tools, the difference in vibration exposure measured in tilted (tilted in 45° for brush cutter, and tilted in 90° for hedge trimmer) and normal holding positions is statistically significant (Wilcoxon test, $p < 0.05$).
2. A correlation between the usage time of the examined brush cutters and their vibration exposure was found (Spearman rank correlation, $r = 0.922$, $p(\text{two tailed}) = 0.000$). Increasing the usage time of the examined brush cutters resulted in greater vibration exposures.
3. I produced an *HvLab* computer code to synthesise vibration spectra of real horticultural tools. The synthesised spectra were then used to measure the vibration transmissibility of anti-vibration gloves with the aid of an electrodynamic shaker. The following conclusions have been drawn:
 - a) There was a statistically significant difference in transmissibilities between the standard test method and the transmissibilities obtained with the synthesised tool spectra (Friedman and Wilcoxon tests, $p < 0.05$). Therefore, the standard test spectra do not provide useful predictions of the vibration attenuation likely to occur when a glove is tested with a synthesised horticultural tool spectrum.
 - b) Depending on the test subjects, the examined four anti-vibration gloves generally increased the transmitted vibration to the hand at lower (< 150 Hz) frequencies when the synthesised tool spectra were used.
 - c) After a detailed comparison of the coefficients of variation of the glove transmissibilities, the difference in vibration transmissibility was found to be generally smaller between gloves than between subjects (for spectra M, R, AV chainsaw, nonAV chainsaw, brush cutter old, brush cutter new). Therefore, the most important factor that has an influence on the effectiveness of an anti-vibration glove is the inter-subject variability, which is not defined in the standard method.

- d) The Spearman correlation coefficients did not indicate any relationship between the size of the test subjects' hand and the effectiveness of the anti-vibration gloves ($p(\text{two-tailed}) < 0.05$).
- e) A novel and systematic investigation of the effect of vibration magnitude and handle push force on the vibration reduction performance of a set of gloves was carried out. A positive correlation between the change of vibration transmissibility of the gloves and the handle push force (Spearman rank correlation, $r=0.943$, $p(\text{two-tailed})=0.005$ for Glove2 and 4, and $r=1.00$, $p(\text{two-tailed})=0.000$ for Glove1 and 3) was found. The Friedman and Wilcoxon statistical tests showed a significant difference in transmissibilities measured with different handle push forces. Thus, greater handle push force results in greater vibration transmitted to the hand.

5. CONCLUSIONS, RECOMMENDATIONS

The vibration generated by small hand-held power tools can be a source of vibration induced injuries in the hand and arm.

I investigated the vibration exposure of tools typically used in horticulture in order to assess their effect and risk on the tool user. The results show that extended use of these tools increases the risk of vibration-induced injuries independent of the anti-vibration system design of the tool. The risk arises not only for the high vibration magnitudes transported to the hand, but also for the dominant low frequency components of the vibration. Huge differences were presented in vibration exposures even among similar tools; therefore, the choice of the right tool is a very important preventative method. Besides the reduced risk, the daily duration of the work with such tool can be extended.

The dominant factors in the on set of hand-arm vibration syndrome are the vibration characteristics and the duration of exposure. My results revealed an increased vibration exposure with increasing the usage time of a brush cutter. The examined brush cutters exceeded the vibration action value after around 250 hours, but remained quite constant after 1000 hours of usage. Running follow up measurements on vibration exposure with several types of tools can help to define service guidance and improved manuals.

The manufacturer must declare the vibration emission of the tool by performing measurements or by estimating the vibration emission using similar tool vibration emission data. I showed that the hand-arm vibration generated by a used tool in real working conditions could be different than was expected according to the data provided by the manufacturers for a new tool. As a result, the vibration emission data might underestimate the daily vibration exposure of the user of the machine.

There are several ways of reducing or minimising the vibration generated by hand-held horticultural tools. One of the cheapest solutions could be the anti-vibration gloves. One of the aims of my doctoral work was to investigate the effectiveness of gloves using synthesised horticultural tool spectra. Since the anti-vibration gloves usually do not proved significant reduction below 150 Hz (Griffin 1990), I found inefficient the examined gloves in reducing the low frequency dominant synthesised horticultural tool spectra in this frequency range. Knowing the vibration characteristics of the tool would help to choose the right glove.

The vibration reduction performance may depend on several factors. The findings of this study indicate that the dynamics of the glove, or the dynamics of the hand, or the dynamics of both the glove and the hand vary when the push force varies. The high dependence of glove transmissibility on the force indicates that the vibration isolation of some gloves will be improved by applying a force as light as the working conditions allow.

The results of my experiments show that inter-subject variability can have a greater influence on the vibration reduction performance of a glove than the characteristics of the glove. Further work is required to investigate the effect of human anthropometrics on vibration transmissibility

of a glove. Understanding the vibration transmission mechanism would help not only to increase the reliability of the test methods but also to improve the vibration reduction methods.

During my PhD work, I performed the vibration measurements according to international standards. However, several problems were identified related to the test methods described in these standards. I summarise below my observations and suggestions for the revision of ISO 5349:2001 standard:

- The standard does not describe the required measurement duration for each tool. Since the vibration characteristics have a great influence on measurement results obtained with different measurement duration, it would be useful to describe the minimal measurement time for typical groups of tools. In my experiments with the lawn mower, 20-second measurement duration found to be representative and repeatable. Although I assumed that this measurement duration would have been a good choice for other tools, further studies are required to verify this finding.
- The holding position is not described during the vibration exposure assessment. The experiments with hedge trimmer and brush cutter indicated the importance of the holding position. I would recommend describing a standard holding position for each group of tools that would be representative of real working conditions and performing the vibration exposure evaluation according to that requirement.
- Because of the high inter-subject variability observed among the vibration exposure values of the tool users, using only three subjects could be a source of inaccuracy; the reliability of the standard test might be increased by using more subjects even if less repeats per subject were performed.
- It was noted that the palm adapter easily altered its position during the vibration exposure measurements and this could be a source of the high inter-subject variability. Therefore fixing the accelerometer on the horticultural tool handle might increase the repeatability.
- It was clear from my results that the examined horticultural tools had at least two dominant vibration axes. I would not recommend the single axis vibration measurements on horticultural tools.

From the findings of the present study the following recommendations are given for the revision of ISO 10819:1996 standard:

- The standard test does not provide useful predictions of the vibration attenuation likely to occur when a glove is used with a specific tool. The currently standardised method of evaluating the effectiveness of anti-vibration gloves could be improved by using tool-specific spectra: a glove that passes the test might be labelled accordingly, such as a ‘brush cutter anti-vibration glove’.
- The grip and push force applied on the handle is described in the standard. However in real working conditions, much higher values could occur. It was shown that different push forces than the standard significantly influenced the vibration reduction performance of anti-vibration gloves. It would be desirable to test the gloves with more push and grip force combinations.

- The standard test method does not take into account the importance of inter-subject variability that had the greatest influence on glove transmissibility. The present findings suggest that using only three subjects could be a source of inaccuracy; the vibration attenuation performance can be underestimated or overestimated when measuring with only a few subjects. The reliability of the standard method could be increased by using more subjects.

REFERENCES

- Aldien Y., Marcotte P., Rakheja S., Boileau P.E. (2006): Influence of hand forces and handle size on power absorption of the human hand–arm exposed to z_h -axis vibration. *Journal of Sound and Vibration*, 290 (3–5):1015–1039. p.
- Eurofound (2005): Fourth European Working Conditions Survey. European Foundation for the Improvement of Living and Working Conditions. Forrás: <http://www.eurofound.europa.eu/publications/htmlfiles/ef0698.htm>
- Griffin M.J. (1990). Handbook of human vibration. London: Elsevier Academic Press
- Griffin M.J. (1998): Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration. *Occupational Environmental Medicine*, 55: 340–348. p.
- ISO 10819:1996: Mechanical vibration and shock—hand-arm vibration—method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Organization for Standardization, Geneva, Switzerland
- ISO 5349:2001: Mechanical Vibration. Measurement and evaluation of human exposure to hand-transmitted vibration. International Organization for Standardization, Geneva, Switzerland

PUBLICATIONS OF THE AUTHOR IN THE TOPIC OF THE THESIS

Scientific Journal papers:

László H.E. (2007): The effect of wear of petrol engine power brush cutters on their vibration exposure. *International Journal of Horticultural Science*, 13 (2): 37–44 (ISSN 1585-0404)

László H.E. (2010): Measuring the vibration of a brush cutter in different operational modes. *International Journal of Horticultural Science* IN PRESS

Conference full papers in hungarian

László Helga Elvira (2006): Kiszégek rezgéselemzése. In: *Összefoglaló MTA Kutatási és Fejlesztési Tanácskozás Nr. 30.* (ISBN: 9636114374), Gödöllő, Magyarország. II. kötet 126-130.p.

László Helga Elvira (2007): A kertészeti kiszégek rezgésvédelmének helyzete Magyarországon. In: *Összefoglaló MTA Kutatási és Fejlesztési Tanácskozás Nr. 31.* (ISBN: 978-9636114435), Gödöllő, Magyarország. 199-203. p.

Conference abstract in Hungarian

László Helga Elvira (2009): Kézi kiszégek rezgésterhelésének csökkentési lehetőségei a kertészetben. In: *Összefoglaló Lippay János-Ormos Imre-Vas Károly Tudományos Ülésszak* (ISBN 978-963-503-397-3), 2009. Október 28-30. 190-191.p.

Conference full paper in English

H.E. Laszlo, M.J. Griffin (2009): Measuring the effectiveness of anti-vibration gloves with chain saw vibration. In: *Proceedings of Synergy and Technical Development International Conference* (CD ISBN 978-963-269-112-1), 30 August-03 September, Gödöllő, Hungary. P6-246. p.

H.E. Laszlo (2010): Measuring the vibration of a hedge trimmer in different operational modes. In: *Proceedings of Spring Wind 2010 Conference* (ISBN 978-615-5001-05-5), 25-27 March, Pécs, Hungary. 280-284.p.