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A parameter study on measuring hand-arm vibrations of an impulsive vibrating tool applying the international standard

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Abstract
In daily life, many activities expose us to hand-arm vibrations (HAV). The characteristics, such as frequency components or level, of these vibrations vary substantially. At high levels some can cause changes to the hand-arm system, which are grouped under the term hand-arm vibration syndrome (HAVS). Hence, there are multiple standards on the subject of measuring, evaluating and simulating HAV. In these, many cases are covered with specific instructions, but not all. This leaves leeway in measurements. Additionally, previous studies have shown largely varying results, some even on the same device. The assessment of the risks for the hand-arm system depends both on accurate measurements and knowledge of the influences here-on. The leeway left in the specifications in the standards may be at least part of the origin of the variance in the measured results. In a measurement and comparison of previous studies, influencing factors are to be determined. The goal is an appraisal of the extent of their effect.
Keywords: Hand-Arm Vibration, Shock, Measurement

1 INTRODUCTION

Many studies have been concerned with the measurement and simulation of hand-transmitted vibration. Several factors influence the measured results of the hand-arm vibration (HAV) and their transmission to the hand-arm system (HAS). The current international standards [[1], [2], [3], [4]] seem to leave leeway in their specifications for the measurement and the evaluation of the measured signal. Results in the literature on measurements of HAV often show a standard deviation of up to almost 50% of the mean value of the HAV [6].
Hence, this study applied the international standards and took the current state of research into account in order to evaluate the vibration of an impulsive vibrating tool. Furthermore, the intend is to analyze influencing parameters in measuring impulsive HAV.

2 STATE OF THE ART

In this study, the standards ISO 5349, ISO 15694 and ISO 8662-11 are being considered, as well as previous research on measuring hand-arm vibrations.

2.1 Standards

There are several standards regarding the measurement and evaluation of hand-arm vibrations. ISO 5349 [[1], [2]] contains a standardized measurement procedure for tool vibrations as well as instructions on their evaluation. It is split in two parts, the instructions and the frequency weighting W_h for the measured vibration, a total vibration value and a brief risk evaluation of this value are in the first part. The second one deals with the practical appliance of these. In part one, it requests the following things to be listed when evaluating hand-arm vibrations: name of the subject exposed to vibration; the tools that cause exposure to vibration; power tools, used tools or workpieces; location and orientation of the accelerometer; mean values of vibration in one direction; total vibration value for each tool; daily duration of operation for each tool; daily vibration exposure.
Many of these are values calculated from the measured acceleration $a(t)$. Then is this bandpass filtered and fre-

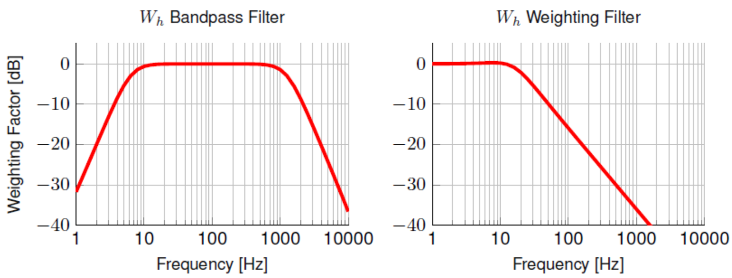

Figure 1. W_h bandpass and frequency weighting filter curves, adapted from Zechmann [5], with the cut off frequencies $f_{W_h,lowpass} = 6.31$ Hz and $f_{W_h,highpass} = 1258.9$ Hz

quency weighted, these filters have been plotted using MATLAB and are shown in Figure 1. The combination of the bandpass and the weighting curves is shown in Figure 2. The filtered signal of each vibration direction, $a_{hwi}(t)$, is used to calculate the total vibration value. As a first step the root mean square (r.m.s.) value a_{hwi} is determined for each direction i by means of Equation 1

$$a_{hwi} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} a_{hwi}^2(t)dt} \,. \tag{1}$$

Then the total vibration value is formed by the sum of squares of the three r.m.s. values as shown in Equation 2

$$a_v = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \,. \tag{2}$$

If not all three directions can be measured, the standard supplies a correction factor.
In order to estimate the risk posed by HAV, the daily vibraion exposure is calculated by Equation 3, in which every total vibration value of each activity is considered for its respective time T_i and T_0 as the reference duration of 8 hours in seconds

$$A(8) = a_{hv(eq,8h} = \sqrt{\frac{1}{T_0} \sum_{i=1}^{n} a_{hvi}^2 \cdot T_i} \,. \tag{3}$$

The standard also supplies $A(8)$ values that cause vibration induced white finger syndrom in 10% of the people over varying durations.
In order to reduce uncertainties in the evaluation of single impact hand-arm vibration, the standards ISO 15694 and ISO 8662-11 have been developed. The latter one defines a measureing method for nailers, while ISO 15694 includes a new filter function as well as new values, which describe different aspects of the vibraton.
The general requirements in ISO 15694 [3] are the same as in ISO 5349. One of the main differences is that it is only required to measure in the direction of the hit. Furthermore, the following data are required: number of impacts during measurement (n_{sh}); interval mean, $flat_h$-rated acceleration ($a_{hF,RMS,3}$); interval mean, W_h-rated acceleration ($a_{hw,RMS,3}$). And these values are optional to be reported: vertex value of the $flat_h$-rated acceleration (CF_h); peak value of the $flat_h$-rated acceleration ($A_{hF,PV}$); shock-content-quotient of the $flat_h$-rated acceleration (SC_h); shock-content-quotient of the W_h-rated acceleration (SC_{hw}); peak value of the gliding mean, $flat_h$-rated acceleration and the time constant; ($a_{hF,MTVV,\tau}$ and τ); over-energetic mean, $flat_h$-rated acceleration value ($a_{hF,RMQ,3}$, with RMQ as root-mean-quad, the 'over-energetic' mean value of a signal); over-energetic mean, W_h-rated acceleration value ($a_{hw,RMQ,3}$).
Similar as in ISO 5349 the measured acceleration is bandpass filtered with the $flat_h$ filter shown in Figure 3.

It corresponds to the band limiting filter W_f of ISO 5349 which should not be confused with weighting filter W_h.

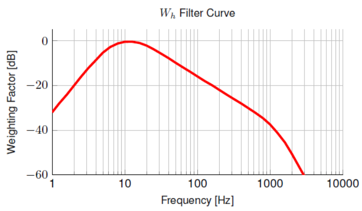

Figure 2. Complete W_h filter curve

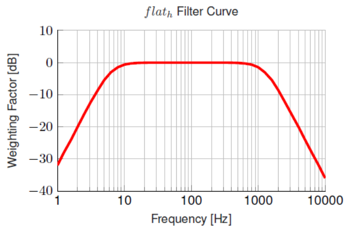

Figure 3. $flat_h$ filter curve, with the cut off frequencies $f_{flat_h,lowpass} = 6.31$ Hz and $f_{flat_h,highpass} = 1258.9$ Hz

In order to obtain the values listed above, the r.m.s.-acceleration $a_{hF,RMS,T}$ and $a_{hw,RMS,T}$ within a time interval T has to be calculated for both weightings, the $flat_h$ and the W_h. T hast the constant value of 3 s

$$a_{hF,RMS,T} = \sqrt{\frac{1}{T}\int_0^T a_{hF}^2(t)dt} \qquad \text{and} \qquad a_{hw,RMS,T} = \sqrt{\frac{1}{T}\int_0^T a_{hw}^2(t)dt}\,. \tag{4}$$

These two equations calculate the energy-equivalent vibration value. With the following two, one calculates the over-energetic mean acceleration values or root-mean-quad (r.m.q.) values, which ephasises higher amplitudes in the signal more than the energy-equivalent vibration value

$$a_{hF,RMQ,T} = \sqrt[4]{\frac{1}{T}\int_0^T a_{hF}^4(t)dt} \qquad \text{and} \qquad a_{hw,RMQ,T} = \sqrt[4]{\frac{1}{T}\int_0^T a_{hw}^4(t)dt}\,. \tag{5}$$

The shock-content-quotient is the ratio between the energy-equivalent mean value and the over-energetic mean value of the acceleration and determined for both weightings:

$$SC_h = \frac{a_{hF,RMQ,T}}{a_{hF,RMS,T}} \qquad \text{and} \qquad SC_{hw} = \frac{a_{hw,RMQ,T}}{a_{hw,RMS,T}}\,. \tag{6}$$

Apart from specifications on the setup with the accelerometer and post-processing with a filter, the ISO 8662-11 [4] gives instructions regarding the body posture of the operator of the tool. The operating person must stand upright or almost upright, has to operate the tool comfortably while maintaining an angle between the upper and lower arm between 100° and 160°. Furthermore, the workpiece must lie in a bed of sand with the dimensions being at least 600 mm x 600 mm x 400 mm. The nail or staple must be at least 50 mm away from the sides of the workpiece. The workpiece must be 1.2 times as thick as the length of the staple or nail. It is required that the measurement is done five times by each of the 3 subjects, who trigger the tool 10 times in 30s per measurement. If a measurement could not be conducted as instructed, the vibration value can be corrected as follows:

$$a_{h,w,3s} = a_{h,w} \cdot \sqrt{\frac{T}{3 \cdot n}}, \tag{7}$$

with $a_{h,w}$ being the weighted root mean square value of the incorrect measurement. It is corrected with the square root of the fraction of the measurement duration divided by three times the number of hits.
After weighting the signal, applying the chosen filter, the mean value and the sandard deviation is calculated for each subject as well as the overall mean value of the vibration.

The purpose of ISO 5349 is to estimate the risk posed by hand-arm vibration at the workplace, whereas ISO 15694 focuses on single hits and ISO 8662-11 is specified for nailers. Hence, the evaluation of the measured signal differes among the standards as well as some of the measuring instructions.

2.2 Research

Apart from the above described standards, many studies on HAV have been published, of which not all apply the standards described above.
A study by Ainsa [6] has shown that the position and angle of the accelerometer relative to the respective coordinate system influence the measurement result. Only ISO 8662-11 specifies the position in front of the index finger and thumb on the handle as mandatory, the ISO 5349-2 suggests a position as close to the index finger and thumb as possible.
In the same study, Ainsa [6] found that the previously named factor together with the fixing method of the accelerometer lead to the greatest variation in the results. The fixing options include bolting the accelerometer to the tool, glueing it, clamping it or holding it with an adapter. The assumption would be that the stiffer the connection between the accelerometer, the higher the measured vibration values. Yet, in Ainsa's study this was not the case for all measurements.
Several studies have shown an influence of the grip and the push force on the measurement [[7], [8], [9]]. So far, the authors have not found any indication that there had been any studies on these forces with a tool, like it is used for these measurements. In most cases, the acceleration and those forces have been measured on a specifically designed handle [[6], [7], [10], [11], [12], [13], [14]]. As they could only be evaluated qualitatively, they are not considered in this study.
The body posture has mainly been investigated regarding the mechanical impedance of the hand-arm system [e.g. in [6]], which influences the transmission of the vibration within the human body, but is not assumed to influence the vibration measured on the tool. This is furthermore influenced by the dimensions and other properties of the hand-arm system of the operator.
Another factor considered in research is the measurement duration. Both Kaulbars [15] and Marchetti et al. [16] showed in their respective studies a decrease in the vibration value with an increase of the time window. As the high vibration peak is followed by an absence of vibration, the larger the time window is, the more the vibration value decreases and hence, the tool's vibration is increasingly underestimated. The mandatory standard ISO 5349 only advises to keep the measurement duration as short as possible before and after the strike of the tool. The current standards for slowly striking tools, ISO 15694 and ISO 8662-11, give more specific instructions on the measurement duration, but are not yet mandatory. In order to get a better estimate of the risk of HAVS, Lindström and Dong proposed to use the absorbed energy [[10], [11], [17]].
Furthermore, the vibration characteristics are being taken into account. Focusing on the impulsive vibrations, Louda [18] proposed a subdivision of the group of impulsive vibrating tools depending on their frequency spectrum. One group has the highest vibration amplitudes above 1000 Hz and the second one has them below 100 Hz. This supports the weighting which attenuates frequencies above 1200 Hz given by ISO 5349 and the lowpass filter of ISO 15694 with a cutoff frequency of 1250 Hz. In [10], Dong found that high frequencies do not penetrate the hand-arm system as much as low frequencies do.

3 MEASUREMENT

In light of the previous research, an impulsive vibration tool was selected for this study. Thereupon, the parameters to be evaluated were chosen and the measurement conducted in accordance with the standards.

3.1 Tool and parameter selection

The tool chosen for the measurements is an electric stapler, the model Bosch Akku Tacker PTK 3,6 LI. It's given total vibration value is below 2.5 $\frac{m}{s^2}$ and the staples used are of 11.4 mm width and 10 mm depth.
Considering the influencing factors mentioned in the previous section, the parameters that were analyzed are the

position of the accelerometer, the fixing mechanism and the measurement duration. Three different positions on the tool were chosen and shown in detail in the set-up description. By applying all three accelerometers at the same time, the weight of the set-up was increased slightly, but a better comparability was given. The fixing mechanisms used are a tie-wrap and glueing. Furthermore, the measurement duration was varied between 3s, 1s and the time between the 1%-threshold of the maximum.

3.2 Measurement set-up

The measurements were conducted in the facilities of Müller-BBM GmbH in Planegg. The electric stapler shown in Figure 4 was used with the original staples described in the previous section. Three uniaxial accelerometers of B & K (B & K 4500 A and B & K 4501 A), the amplifiers B & K type 2647-A for the ones on positions one and two and B & K type 2635 for the third one, the measuring system PAK MKII and the software PAK 5.9 were used. The sampling frequency used was $f_s = 32768$ Hz. The positions of the sensors are shown in Figure 4. At position one and three, the accelerometers were initially fixed with tie-wraps, while the one on position two was glued on with Loctite 454. During one measurement, the sensor at position three was glued on, while the other two remained unchanged.
The pieces of wood, in which the staples were sunk, used had the following dimensions: $250 \cdot 120 \cdot 19$mm. And the bed of sand in which these were placed had the dimensions: $560 \cdot 360 \cdot 50$mm. Hence the set-up meets the requirements of ISO 8662-11 apart from the minimum dimensions of the sandbed.

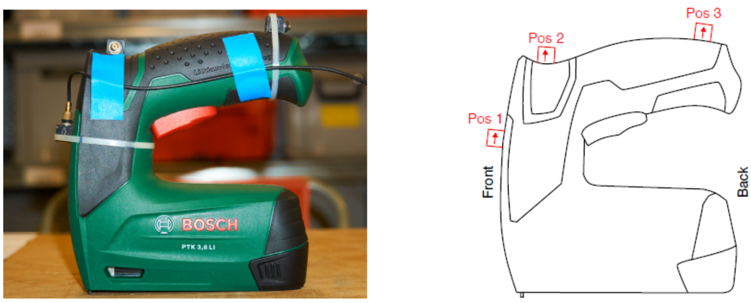

Figure 4. Electric stapler Bosch Akku Tacker PTK 3,6 LI and the positions of the three accelerometers

3.3 Performance of the measurements

The measurements were carried out by five participants, which exceeds the number of required test subjects in ISO 8662-11. The participants practiced prior to the first measurement in order to experience the pressure such that the staples are sunk completely. Furthermore, they were instructed to only hit the homogeneous areas of the wood, as one without has not been available.
Each participant then completed five measurements of 30s including 10 triggerings per variation.

3.4 Evaluation of recorded data

According to the above described standards, the raw data was bandlimited and frequency weighted. Afterwards the r.m.s.-acceleration was calculated over a specific time window. This was done for both filter functions, which were adapted from Zechmann [5] and with all three time windows described in the previous sections. All the calculations were done in MATLAB. Altogether, the following values were determined: $a_{hw/hF,RMS,T}$ $[\frac{\mathrm{m}}{\mathrm{s}^2}]$ r.m.s. value; $a_{hw/hF,RMQ,T}$ $[\frac{\mathrm{m}}{\mathrm{s}^2}]$ root-mean-quad value; $a_{hw/hF,PV}$ $[\frac{\mathrm{m}}{\mathrm{s}^2}]$ peak value; $a_{hw/hF,MTVV}$ $[\frac{\mathrm{m}}{\mathrm{s}^2}]$ maximum transient vibration value; $CF_{hw/hF}$ [-] crest factor; $SC_{hw/hF}$ [-] shock content quotient; $a_{hw/hF,3s}$ $[\frac{\mathrm{m}}{\mathrm{s}^2}]$ single hit value normalised to 3 seconds.

4 RESULTS

The results of the measurements are shown below.

4.1 Time signal

An examplary unprocessed recorded acceleration at position two is shown in Figure 5. There is a difference in the unweighted peak value of the acceleration among the positions, at position two it is above $10000\frac{\mathrm{m}}{\mathrm{s}^2}$ and at the other two positions it is around $3000\frac{\mathrm{m}}{\mathrm{s}^2}$. Figure 6 shows the first impact of every test subject from position 2 in one measurement. The two plots in Figure 6 have different scalings in order to illustrate the vibration before the impact (top) and the impact itself (bottom).

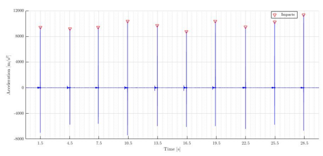

Figure 5. Unweighted acceleration of measurement 3, position 2, test subject 2

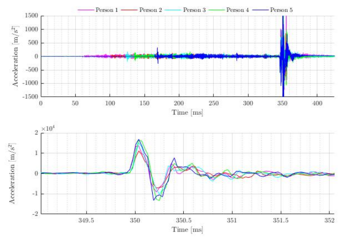

Figure 6. Detailed view of one impact

4.2 Spectra

The spectra hardly differ between measurements, some differences can be observed among the measuring positions, as can be seen in Figure 7. The slope of the spectra between 80Hz and 105Hz is greater for positions one and two than for position three. Comparing the unweighted spectrum with the spectra after applying the respective filters in Figure 8, the attenuation of higher frequencies by the W_h-weighting relative to the $flat_h$-weighting and the unweighted spectrum becomes apparent.

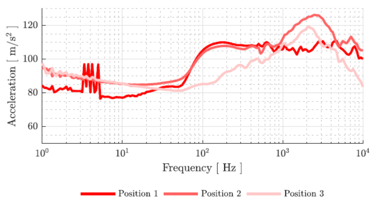

Figure 7. Spectrum of different positions (unweighted acceleration)

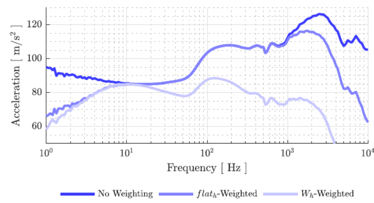

Figure 8. Spectrum of different weightings

4.3 Vibration values

Comparing r.m.s.-values of the two weightings for the different measurements, positions and fixing methods, on average there is roughly a factor 18 between the $a_{hw,RMS}$ and $a_{hF,RMS}$ for all time windows that were applied. The W_h-weighted r.m.s.-values range from 2.5 to $2.8\frac{\mathrm{m}}{\mathrm{s}^2}$ for the 3s window, from 4.2 to $4.8\frac{\mathrm{m}}{\mathrm{s}^2}$ for the 1s window and for the 1% threshold window from 7.6 to $8.6\frac{\mathrm{m}}{\mathrm{s}^2}$. The root-mean-quad values differ by a factor of roughly 35. These differences are smaller for the crest factor $CF_{hw/hF}$, which varies by a factor of about 2.8. Almost the same applies to the shock content quotient $SC_{hw/hF}$, for which the factor is only about 1.8 on average. Between the W_h-weighted peak value and the $flat_h$-weighted one, however, is a factor of roughly 52. The factor 18, which could already be observed in the r.m.s.-values, shows again in the single hit value normalised to 3 seconds $a_{hw/hF,3s}$. In all cases, the differences between the measurements appear rather small compared to

the standard deviations.
These differences between the weightings combined with the slightly different spectra at the three positions result in a different relation between the positions depending on the applied weighting. For the $flat_h$-filter, position two gives the highest r.m.s.-values, whereas it is roughly on a level with position one for the W_h-weighting.

5 DISCUSSION

When comparing the spectra, the peaks at the low frequencies cannot be explained without further investigations. These peaks do not appear systematically. The reason for them is likely an error in the measurement chain or the evaluation. Another difference in the spectra in Figure 7 is the lower slope of the vibration amplitude between 80Hz and 1kHz for position three. It is next to the little finger, at the handle's end (see Figure 4). An explanation might be that one of the handle's eigenmodes lies within that frequency interval, that dampens the vibrations at this position for that frequency. One parameter with smaller influence on the results than initially expected is the mounting of the accelerometer. In summary, the biggest influence on the spectra is given by the position of the accelerometer.
The shock content quotient and crest factor, as well as the r.m.s.-values, largely depend on the weighting of the acceleration. $flat_h$-filtering leads to higher values, which is most likely due to the high frequency content of the signal at the peak of the impact. Furthermore, only subject 2 always sank the staples completely and has the lowest vibration values in three out of the four measurements. ISO 8662-11 prescribes to sink the staples completely. With this condition unfulfilled for all but one subject at all times, it may be discussed whether this represents the average use of the tool. Hence, the measured r.m.s.-accelerations of this test subject might be more representative.
Comparing the measuring positions, it is not clear, why position two has lower vibration values than position one, when the signal is W_h-weighted. The measurement results of this study showed a decrease in impulsiveness, when the high frequencies are filtered out.

6 CONCLUSIONS

Impulsive or shock hand-arm vibrations are a topic of current research. In this study, several influencing factors regarding the evaluation of these have been investigated. Using three uniaxial accelerometers on three different positions, measurements were conducted on an electric stapler. Additionally, the mounting of the accelerometers was varied as well as the applied time window and filter, in order to investigate their respective influences.
The differences among the three positions of the accelerometers are bigger than the ones due to the change in the fixing method. However, different mountings may have advantages and disadvantages in different situations. The differences in the r.m.s.-acceleration and the spectra were the biggest between positions. It depends on the frequency weighting, at which point the accelerations have the highest amplitude. The $flat_h$-weighting leads to consistently higher accelerations than the W_h-filter. Though, no statement can be made, which of the two estimate the vibration transmitted into the hand-arm system the best.

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