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An Evaluation of the Standardized Chipping Hammer Test Specified in ISO 8662-2

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Objectives: Prolonged exposure to severe chipping hammer vibration may cause hand–arm vibration syndrome. A reliable test method is required to select appropriate tools and assist in the development of better chipping hammers. In the present study, the ISO standardized test method (ISO 8662-2, 1992) was examined through an investigation of the vibration characteristics of chipping hammers operating on the energy absorber specified in the standard.

Methods: The energy absorber and test setup were designed and constructed based on those specified in the standard. The experiment employed six subjects and used two pneumatic chipping hammers and three different feed forces (50, 100 and 200 N). The subject posture was the same as that specified in the standard.

Results: The vibration emission at the tool dominant frequency (or air blow rate) generally declined with an increase in feed force, thus decreasing the frequency-weighted accelerations. The increase in feed force, however, resulted in an increase in the unweighted vibration emission at high frequencies. The chipping hammer vibration emission operating on the energy absorber at the high feed force (200 N) was inconsistent.

Conclusions: The measurement method has a good repeatability except at a high feed force. The feed force has a significant effect on the vibration emission. The single feed force specified in the standard may not be sufficient to test the tool behaviors. Multiple levels of feed force should be used for the chipping hammer test. Doing so may provide a more appropriate basis for tool screening.

Keywords: chipping hammer; tool vibration measurement; hand-transmitted vibration; hand–arm vibration

INTRODUCTION

Pneumatic chipping hammers are typical percussive tools and have been widely used to dress metal castings, cut stones, set packing material in pipe joints and to repair concrete structures. These tools can generate considerable hand-transmitted vibration (Reynolds *et al.*, 1984; Starck, 1984; Hewitt, 1995). Prolonged exposure to such vibration may cause an array of sensorineural, vascular and musculoskeletal disorders in the hands and arms. These disorders have been collectively called hand–arm vibration syndrome (HAVS) (for more information on HAVS see Griffin, 1990; Pelmear and Wasserman, 1998). As pressures to reduce occupational vibration exposures have increased during the past decade, power tool manufacturers in some countries have been required to declare the vibration emission of their tools, and employers are also expected to emphasize the selection of 'suitable' tools as a part of their occupational safety and risk management programs (EU, 2002).

The development and selection of suitable chipping hammers require a reliable and effective test method to assess tool vibration severity. Several different methods have been proposed for these tool assessments. One method requires the chipping of a uniform layer of mild steel, 2 mm thick, with a representative chipping hammer (Bitsch *et al.*, 1986). Because measuring vibration on a chisel is extremely difficult (Clarke *et al.*, 1986), Reynolds and Markle (2001) developed an indirect method to measure these impact vibrations. This method requires the

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installation of a steel block affixed to a soft spring–damper system such as a tire inner tube. The acceleration of the steel block is measured while the chipping hammer oscillates the block in the vertical direction. The measured acceleration is then used to derive the acceleration of the chisel as well as the impact force acting at the chisel tip.

In an effort to develop a uniform method, the International Organization for Standardization (ISO) has set forth laboratory test procedures (ISO 8662-2; ISO, 1992) for vibration emission assessments of chipping and riveting hammers. Briefly, a special energy absorber is used to simulate the reaction of a working piece subjected to a vibration stimulus. A chipping/riveting hammer is tested with an anvil-headed bit inserted into the top of the energy absorber. Three human subjects are needed to fulfill the test requirements. Each subject assumes the specified posture and applies a specific feed force to the tool handle during the test. The frequency-weighted acceleration in the dominant vibration axis is required to be measured and used for the tool vibration assessment. The energy absorber is intended to provide consistent and repeatable reactions to the tool's vibration inputs, similar to the reactions of working materials. The tools, however, can generate considerably different vibration magnitudes and characteristics on different working materials. It has been reported that the standardized test results have a poor correlation with field measurement data (Hewitt, 1995) and that there is a large variation of the data obtained from different laboratories (Schenk and Gillmeister, 1998). It is also unknown how the chipping hammer would behave on the energy absorber at different feed forces.

The specific aims of the present study are (i) to determine the fundamental vibration characteristics of two chipping hammers at different feed forces when operated on the energy absorber, (ii) to further identify the major deficiencies and technical problems of the standardized test method and (iii) to explore alternative test procedures for chipping hammer vibration emission assessments.

MATERIALS AND METHODS

Experimental set-up

The chipping hammer test setup used in this study was designed and constructed based on the requirements of the standard (ISO 8662-2; ISO, 1992) and is sketched in Fig. 1. The key feature of the test apparatus is the energy absorber. In accordance with the ISO standard, the energy absorber is composed of a steel tube filled with hardened steel balls. The absorber is firmly mounted on a rigid steel base that is secured to a concrete block. A special anvil-headed chisel bit is required for the test. The bit is inserted

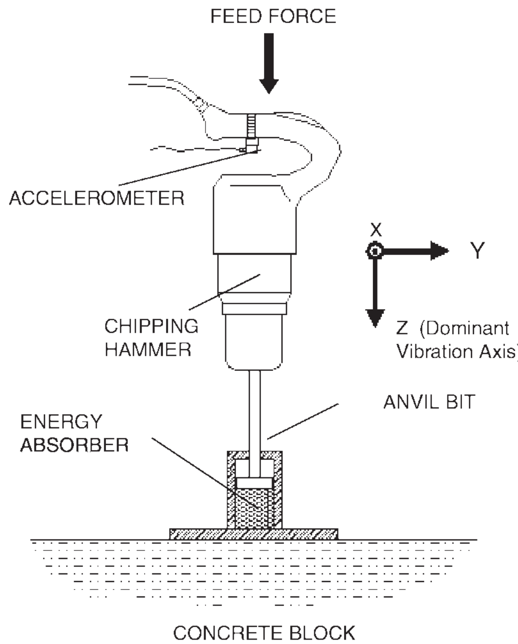

Fig. 1. The measurement setup for the ISO standardized chipping hammer test (ISO 8662-2, 1992).

into the top of the energy absorber and the anvil rests on top of the column of steel balls.

Two new pneumatic chipping hammers (Tool A and Tool B) were used in this study. They weigh 6.6 and 6.9 kg, respectively. The length of the anvil-headed chisel bit was ~30 cm (12 inches). The supplied air pressure was regulated to 689 kPa (100 p.s.i.), as specified by each tool manufacturer.

The measurement of vibration of percussive tools often yields significant DC shifts in the piezoelectric accelerometer output (Kitchener, 1977). The application of a commercially available mechanical filter (B&K UA0059) did not help circumvent the difficulty associated with the DC shift of the triaxial accelerometer (PCB 5611A) used in this study. Consequently, a mechanical filter comprising a 3 mm thick elastomer was configured in an attempt to minimize the DC shift. The triaxial accelerometer was installed on a mounting block and secured to the handle with a hose clamp. The effectiveness of this filter in the dominant vibration direction (vertical direction) was examined by performing measurements with a non-contacting laser vibrometer (Polytec PI, PSV-300H) and comparing the measured response with that acquired from the handle mounted accelerometer. It was found that the filtering effectiveness of the elastomer depended on the tightness of the hose clamp. A good match between the two measurements generally extended from high frequencies to lower frequencies with the reduction of the tightness. It was, however, extremely difficult to eliminate the entire DC shift at low frequencies (<10 Hz)

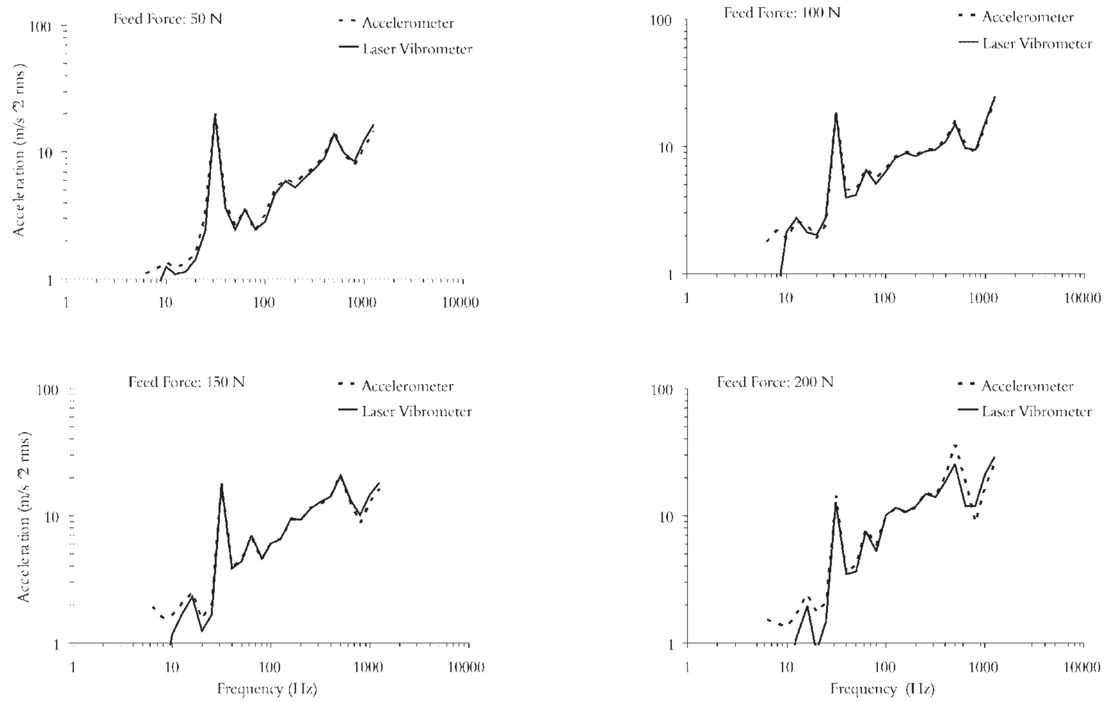

Fig. 2. Comparisons of tool vibration spectra measured with a conventional accelerometer and a laser vibrometer.

without significantly losing some high frequency components. For the purpose of this study, the tightness was adjusted such that the acceleration measured with the accelerometer was generally consistent with that measured with the laser vibrometer at frequencies >10 Hz. This was fairly easy to achieve on Tool A, but difficult on Tool B, probably because Tool B had a lower fundamental dominant frequency (31.5 Hz) than Tool A (40 Hz). Several samples of the comparisons recorded in Tool B calibration are illustrated in Fig. 2. As can be seen, the accelerations from both measurement methods at frequencies >20 Hz are very reasonably consistent. The low frequency components measured with the conventional accelerometer are at a similar level to those reported in the literature (Griffin, 1990), but they are generally higher than those measured with the laser vibrometer. Since these vibration components are at a very low level, the possible errors that could be caused by the residual DC shifts are not critical for the purpose of this study.

A multi-channel data acquisition unit (B&K Type 2816) was used to collect all the vibration signals from the accelerometers. The vibration data collected from this system were expressed as the root mean square (r.m.s.) values of the accelerations in the 1/3 octave frequency bands, with center frequencies from 6.3 to 1250 Hz, as required in the standard.

Study variables

The objective of the ISO standardized chipping hammer test is to determine the vibration emission of the tool when it is working on the energy absorber. Different subjects may generate different test results, which is considered as a random factor in the test. The objective operation variables are the feed force applied to the tool handle and the working time. Because the tool vibration emission does not usually change significantly with time, especially during a short period of operation on the energy absorber, the time is not considered as a study factor. It is unknown how the feed force could affect the test results. The standard specifies the feed force as a function of the tool weight, which may present some problems. To evaluate this, three feed forces (50, 100 and 200 N) were used in this experiment. A force measurement plate (Kistler Type 9286AA) was used to measure the applied feed force. The target feed force was calculated by subtracting the designed feed force from the weight of the subject (in N), as specified in the ISO standardized chipping hammer test (ISO 8662-2; ISO, 1992). A 20 inch computer monitor was placed directly in front of the subject, which displayed a full-screen force strip chart so that he could monitor and control his feed force during the tool operation. The target force was always adjusted to the horizontal center line and the displayed force range was fixed at target force ± 50 N. The displayed time range was 2 s.

Six healthy male subjects recruited from a local university were employed in this study. The physical characteristics of the subjects are listed in Table 1. For this study, the test subjects were instructed to use the same posture as that specified in the chipping hammer test standard (ISO 8662-2; ISO, 1992). Each subject stood on a platform and applied a downward push force on the tool handle. The platform height was adjusted for each subject to ensure proper posture and to maximize comfort. The tool switch was fixed in the 'on' position with adhesive tape so that the subject could focus his attention on the tool operation and maintain a relatively constant feed force. A test assistant used a ball valve at the regulated air supply to control the tool on/off operation during the test. The study protocol was reviewed and approved by the NIOSH Human Subjects Review Board.

Vibration data collection was initiated once the feed force was observed to be stable. The measurement duration in the present study was 15 s (a minimum of 8 s duration is required in ISO-8662-2). The test subjects rested between consecutive trials. The rest period was typically ~1 min.

Six trials were performed for each test combination of feed force and tool. The six trials were divided into two groups (three trials per group). The three trials within each group were performed sequentially. The second group of trials was performed after the first group of trials for each feed force had been completed. The sequence of feed force levels in each group was randomized. The sequence of hammers was also randomized among the six subjects.

Data processing and statistical analysis

The vibration spectra measured on each tool were first analyzed in a two-way repeated measures analysis of variation (ANOVA) to establish the overall significance of vibration frequency and feed force. The ANOVA was done using a mixed model approach with frequency and feed force as fixed effects and subject as a random effect. As also presented in the next section, the interaction between the frequency and the feed force was found to be significant. This indicates that the variation in the vibration magnitude over frequency was generally different across the force levels. To identify the effect at different frequency regions, one-way ANOVAs were performed for the data at each frequency using a mixed model with the force as a fixed effect and the subject as a random effect. *Post hoc* comparisons using Tukey's method were also performed to determine which of the vibration means at the three feed forces at each frequency were significantly different from each other.

As required in the standardized chipping evaluation, the r.m.s. acceleration value of frequency-weighted vibration was calculated using the weighting specified in ISO 5349-1 (ISO, 2001). As additional information for the evaluation, the r.m.s. acceleration value of the unweighted vibration was also calculated in this study. Similar to the analyses of the vibration spectrum, the weighted and unweighted r.m.s. accelerations at the three force levels for the two tools were also first analyzed in a two-way ANOVA and then in a one-way ANOVA and Tukey's test. The mixed models with feed force and tool type as fixed effects and subject as a random effect were also used in this series of ANOVAs. All statistical analyses were performed using MINITAB statistical software (Version 13.1). All the differences of the means were considered significant when $P < 0.05$.

The coefficient of variation (CV = standard deviation/mean) is required as a measure of the quality of the test data in the ISO standardized chipping hammer test (ISO 8662-2; ISO, 1992). The standard requires that the intra-subject CV value for the weighted acceleration on the dominant axis (A_{wz}) should be ≤0.15. The CV value was thus also used in the present study for judging the repeatability of the vibration emission of the chipping hammers on the energy absorber.

RESULTS

Effect of feed force on tool vibration spectrum

A summary of the two-way ANOVA results for each tool's vibration spectrum is listed in Table 2. The results indicate that (a) the feed force highly influences the vibration spectra measured on both tools; (b) the vibration magnitude strongly depends on the frequency; and (c) the effect of the force on the vibration magnitudes at different frequencies varies significantly.

Table 1. Physical characteristics of the six subjects

Subject	Height (cm)	Weight (kg)
1	183	97.5
2	188	91.2
3	185	91.7
4	188	112.2
5	168	63.1
6	185	68.0

Table 2. A summary of the two-way ANOVA results for determining the overall effect of feed force on the vibration spectra of the two tools

Source	df	Tool A		Tool B	
		F	*P*	*F*	*P*
Frequency	23	1692.26	<0.001	1545.89	<0.001
Feed force	2	1312.68	<0.001	1027.32	<0.001
Force × Frequency	46	183.73	<0.001	147.23	<0.001

The average vibration spectra at the three force levels for the two tools are shown in Fig. 3. The figure also illustrates the permitted exposure limits recommended in an American National Standards Institute (ANSI) standard (ANSI S3.34; ANSI, 1986) for risk assessment of hand-transmitted vibration. The vibration components at the low frequencies (<25 Hz) may be discounted because there are residual DC shifts at these frequencies and their values are also relatively low, as mentioned above. The results of the one-way ANOVA and Tukey tests at each frequency from 25 to 1250 Hz are listed in Table 3. The statistical results clearly indicate that the tool vibration components at each frequency at the three forces are generally highly significant. There are only a few specific pairs of Tukey's comparisons that are not significant, which usually occurred in the spectrum intersection zone where the spectra changed their relative magnitudes.

As can be seen in Fig. 3, the peak values at each tool's fundamental dominant vibration frequency or air blow frequency (40 Hz for Tool A and 31.5 Hz for Tool B) generally decreased with an increase in feed force, although the difference between the values at the 50 and 100 N feed forces on Tool A were not statistically significant (see Tukey's test in Table 3 at 40 Hz for Tool A). The vibration components at

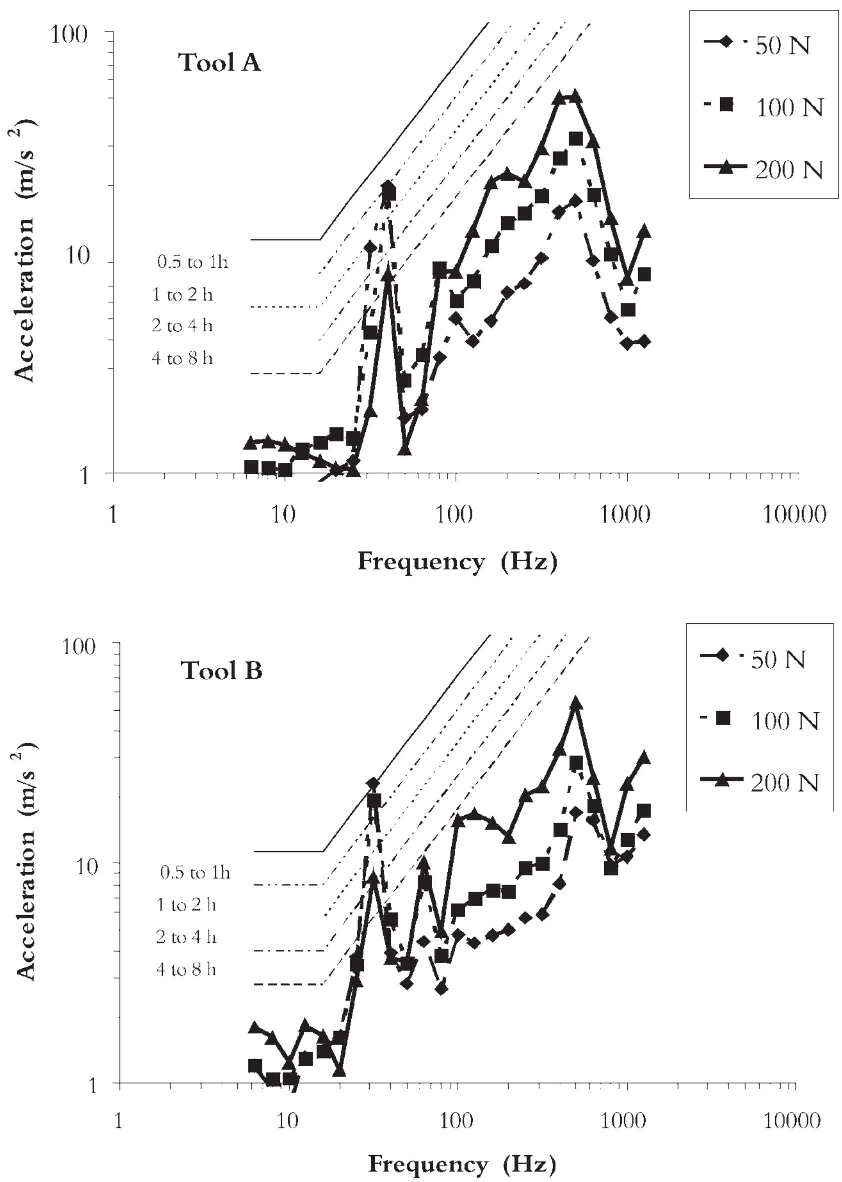

Fig. 3. Average vibration spectra of the two chipping hammers at the three force levels.

Table 3. Results of one-way ANOVAs and Tukey's test for determining the effect of the feed force on the tool vibration spectra

Frequency (Hz)	Tool A			Tool B		
	F	*P*	Insignificant pair(s) from Tukey's test	*F*	*P*	Insignificant pair(s) from Tukey's test
25	21.12	<0.001	50–200 (P = 0.31)	8.29	<0.001	50–100 (P = 0.30)
31.5	227.53	<0.001		199.33	<0.001	
40	133.53	<0.001	50–100 (P = 0.21)	31.77	<0.001	50–200 (P = 0.78)
50	56.28	<0.001		9.83	<0.001	100–200 (P = 0.95)
63	35.33	<0.001	50–200 (P = 0.44)	29.97	<0.001	100–200 (P = 0.055)
80	43.97	<0.001	100–200 (P = 0.86)	24.41	<0.001	
100	21.51	<0.001	50–100 (P = 0.10)	145.91	<0.001	50–100 (P = 0.099)
125	100.90	<0.001		227.45	<0.001	
160	350.51	<0.001		190.99	<0.001	
200	539.66	<0.001		123.74	<0.001	
250	173.99	<0.001		530.15	<0.001	
315	468.34	<0.001		615.41	<0.001	
400	656.64	<0.001		641.42	<0.001	
500	398.06	<0.001		453.77	<0.001	
630	508.04	<0.001		134.13	<0.001	
800	277.12	<0.001		37.87	<0.001	50–200 (P = 0.83)
1000	148.03	<0.001		206.11	<0.001	
1250	283.38	<0.001		151.90	<0.001	

frequencies equal to or higher than 100 Hz, however, generally increased with an increase in feed force.

To quantify the relative difference of the tool vibration spectra at different force levels, the relative differences among the spectra (RD = the absolute difference between the values for each force pair divided by the mean value of the three spectra) at the three forces were calculated. The results are shown in Fig. 4. The difference for the 50 N–100 N pair is generally the smallest at the majority of the frequency points. The relative vibration difference generally increases with the difference between the force levels.

Effects of feed force and tool type on r.m.s. acceleration values

The r.m.s. acceleration values of the frequency-unweighted and frequency-weighted vibrations in the dominant vibration axis are listed in Tables 4 and 5, respectively. To assess the effect of the residual DC shifts on the r.m.s. values at the low frequencies (6.3–20 Hz), the calculations of the r.m.s. accelerations were performed in two frequency ranges (6.3–1250 and 25–1250 Hz). As can be seen in Table 4, the exclusion of the low frequency vibration components has little effect on the unweighted r.m.s. values. Its effect on the weighted r.m.s. values is also less than 5% at the 50 and 100 N feed forces, which would not usually be of great consequence for practical engineering applications. The difference at the 200 N feed force is 8.60% for Tool A and 8.85% for Tool B, which could not be ignored in some applications. For the purpose of this study, however, such a difference is not critical, because the variations of the r.m.s. values would not change the basic conclusions of this study. Furthermore, the actual differences in the r.m.s. values at all three forces is likely to be less than those listed in Table 4 because some of these differences resulted from the inflated low vibration components due to the residual DC shifts. Therefore, either group of the acceleration r.m.s. values can be used to evaluate the effects of the feed force and tool differences.

The acceleration r.m.s. values from both frequency ranges were analyzed separately using the two-way ANOVA to establish the overall significance of the feed force and tool type effects. Because there was significant interaction between the force and tool type in all the cases, the two groups of data were also analyzed separately using the follow-up one-way ANOVA and Tukey's test to determine the significances of the differences at different force levels on each tool and the differences between the two tools at each force level. The statistical results from the two groups of data are basically consistent, which further confirms that it is acceptable to neglect the error due to the residual DC shifts for the purpose of this study. For simplicity, the statistical results from the frequency domain 6.3–1250 Hz are used in the following presentation.

As can be seen in Table 4, the unweighted r.m.s. acceleration values increase with an increase in feed force on both tools (for Tool A, F = 663.30 and P <

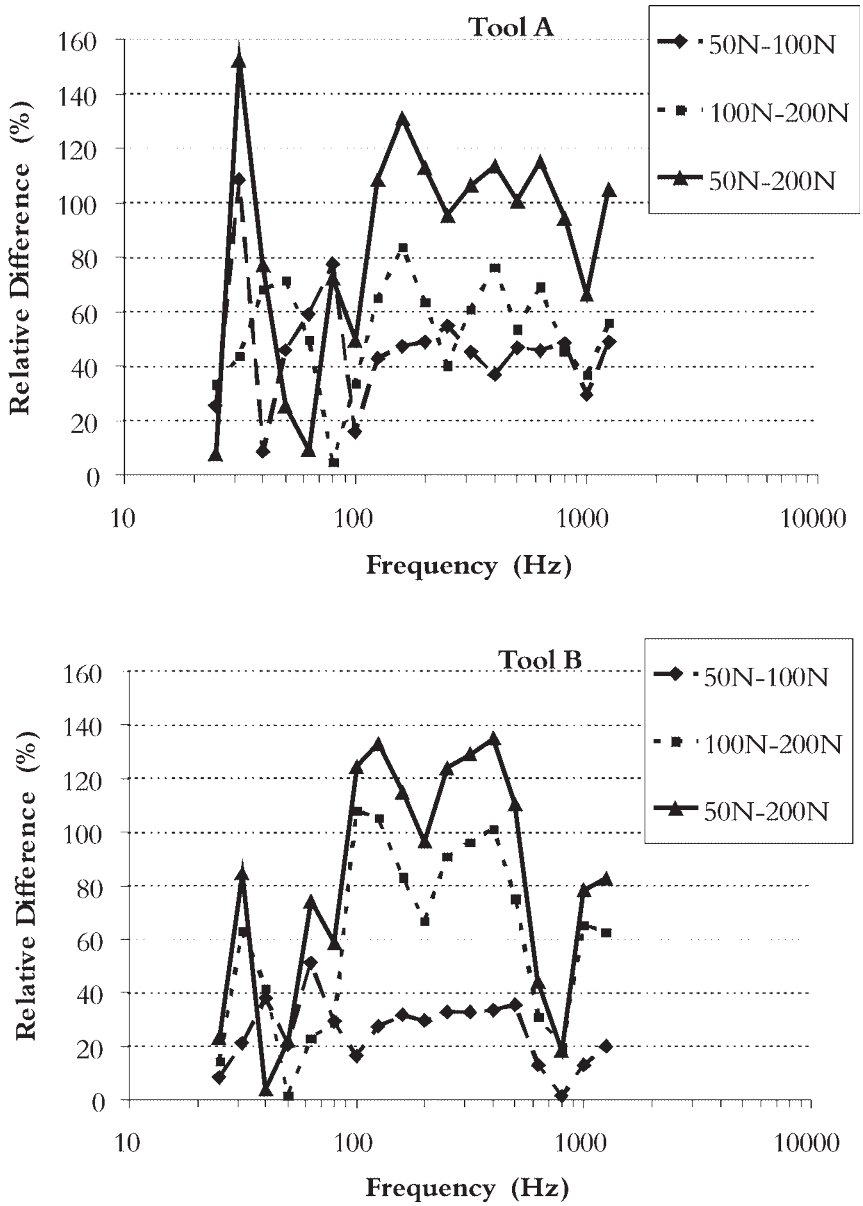

Fig. 4. Relative difference of the three pairs of average vibration spectra at the different feed forces.

0.001; for Tool B, F = 661.23 and P < 0.001), in which the difference between every pair of the accelerations at different forces are significant (P < 0.001) based on the one-way ANOVA and Tukey tests. The effects of the feed force on unweighted r.m.s. values for the two tools are different (F = 14.52, P < 0.001). At 50 N, Tool B had a higher vibration than Tool A (P < 0.001), but the trend was inversed at 100 and 200 N (P < 0.001).

As can be seen in Table 5, increasing the feed force reduces the weighted r.m.s. acceleration value, which is consistent on both tools (for Tool A, F = 70.15 and P < 0.001; for Tool B, F = 70.24 and P < 0.001) and also be highly significant (P < 0.007) in all the Tukey paired comparisons at different force levels. At each force level, the weighted r.m.s. value on Tool B is consistently higher than that on Tool A (P < 0.001). However, the reduction rates of the weighted r.m.s. value as a function of the feed force on the two tools are generally different because the force × tool interaction is significant (F = 4.52, P = 0.014).

Repeatability of the standardized chipping hammer test

The inter-subject CV values and the mean intra-subject CV values of the unweighted and weighted

Table 4. Frequency-unweighted acceleration r.m.s. values

Frequency range used to calculate acceleration r.m.s. value	Unweighted acceleration r.m.s. value (m/s^2)					
	Tool A			Tool B		
	Feed force (N)			Feed force (N)		
	50	100	200	50	100	200
6.3–1250 Hz ($A_{u6.3}$)	37.96	60.95	95.71	41.92	53.44	90.98
25–1250 Hz (A_{u25})	37.90	60.87	95.65	41.81	53.35	90.90
Percent difference[a]	0.16	0.12	0.05	0.26	0.17	0.09

[a]Per cent difference = $2(A_{u6.3} - A_{u25})/(A_{u6.3} + A_{u25})$.

Table 5. Frequency-weighted acceleration r.m.s. values

Frequency range used to calculate acceleration r.m.s. value	Weighted acceleration r.m.s. value (m/s^2)					
	Tool A			Tool B		
	Feed force (N)			Feed force (N)		
	50	100	200	50	100	200
6.3–1250 Hz ($A_{w6.3}$)	10.20	9.16	6.77	12.78	11.43	8.30
25–1250 Hz (A_{w25})	10.03	8.78	6.21	12.52	11.10	7.60
Percent difference[a]	1.63	4.29	8.60	2.11	2.89	8.85

[a]Percent difference = $2(A_{w6.3} - A_{w25})/(A_{w6.3} + A_{w25})$.

Table 6. Values of the coefficient of variation (CV = mean/standard deviation) of acceleration r.m.s. values

Tool	CV	50 N		100 N		200 N	
		A_u	A_w	A_u	A_w	A_u	A_w
A	Mean intra-subject	0.052	0.066	0.081	0.053	0.044	0.156
	Mean inter-subject	0.058	0.033	0.209	0.064	0.110	0.290
B	Mean intra-subject	0.041	0.049	0.069	0.065	0.067	0.148
	Mean inter-subject	0.056	0.089	0.127	0.076	0.073	0.372

A_u, unweighted acceleration; A_w, weighted acceleration.

acceleration r.m.s. values calculated in the frequency range 6.3–1250 Hz are summarized in Table 6. The mean intra-subject CV values of the weighted accelerations for the 50 and 100 N feed forces are ≤0.066, which is less than half of the required value (<0.15) in the standard (ISO 8662-2; ISO, 1992). At 200 N, however, the mean intra-subject CV value is >0.15 for Tool A and is very close to 0.15 for Tool B. The inter-subject CV values of the weighted accelerations at this force level are also obviously greater than those at the 50 and 100 N feed forces. These CV values indicate that there is a large variation in the vibration data at 200 N feed force.

Effect of the subject's physical characteristics

The ANOVA results of this study also revealed that the subject is a significant factor ($F = 73.06$, $P < 0.001$) that affected the test results. The correlations of the subject's weight and height to the r.m.s. accelerations for each tool at each force level were analyzed. The results are listed in Table 7. For the six subjects or the six pairs of data in each combination, the correlation is significant at the 95% confidence level when the Pearson correlation factor is >0.81. As can be seen, the correlation is reliable in only one case (Tool A, weighted acceleration at 100 N feed force). Therefore, the tool vibration r.m.s. values were generally not correlated with these physical characteristics of the subjects.

DISCUSSION

Tool development efforts and tool selection need a reliable test method for chipping hammer vibration assessment. The energy absorber is used as a key device for simulating chipping hammer working conditions in the current ISO standardized chipping hammer test method (ISO 8662-2; ISO, 1992). In order to develop a better chipping hammer test method or improve the existing test protocols, it is essential to understand the characteristics of the chipping hammer vibration emissions that are produced when used with the ISO energy absorber. The present study investigated the vibration emissions of two chipping hammers operating on the ISO energy absorber and produced new information regarding the fundamental characteristics of the standardized test method.

Table 7. Correlation between the subject's physical characteristics and the tool acceleration r.m.s. values

Subject parameter	Pearson correlation factor					
	Unweighted acceleration (N)			Weighted acceleration		
	50	100	200	50	100	200
Tool A						
Weight	–0.75	–0.28	–0.43	–0.55	–0.82	–0.46
Height	–0.77	–0.37	–0.59	–0.18	–0.84	–0.67
Tool B						
Weight	–0.72	0.09	0.45	–0.15	–0.00	–0.30
Height	–0.60	–0.12	0.17	–0.17	0.04	–0.13

For the six subjects used in this study, the correlation is significant ($P < 0.05$) only when the Pearson correlation factor is >0.81.

It is usually very difficult to obtain highly repeatable test data at real workplaces in the field because of the difficulties of controlling all of the many variables associated with complex working environments. As mentioned above, one method of replicating chipping hammer operation in steel work involves chipping off a layer of mild steel from a test piece (Bitsch *et al.*, 1986). While this method may provide a reasonable simulation, it is anticipated that the experimental data would vary greatly because of the difficulties associated with control of the material properties of the test piece, the applied feed force, the chipping orientation, the posture of the test subject and the consistency of the sharpness of the chisel used in the experiment. In addition, it may be inconvenient to setup the test. These are probably the major reasons that this method has not been generally accepted. On the other hand, the energy absorber provides very consistent working conditions for different subjects. It requires little maintenance and can be used repeatedly for the experiment. The absorber can also be fairly uniformly replicated at different laboratories. Therefore, the energy absorber may be an acceptable device for establishing a uniform test setup to be used in laboratory environments for chipping hammer evaluations, if the vibration emission on the energy absorber would be correlated to the tool vibration in its real use.

The results of this study demonstrate that the reproducibility of the vibration emission on the energy absorber is acceptable except at a 200 N feed force. It has been previously reported that the reproducibility of the standard test was generally fairly good and there was no major difficulty in meeting the 15% CV requirement specified in the standard (Hewitt, 1995). This finding suggests that the reproducibility of the energy absorber method recommended in the standard is acceptable, which is one of the essential criteria of the test standard. As also observed in the present study, the vibration emission differences between Tool A and Tool B used in this study are reliable. At the same level of feed force, Tool A consistently produced less vibration than Tool B when judged using the standard specified acceleration weighting function. Accordingly, the ISO energy absorber method appears to provide an acceptable means of comparing the vibration emissions of various chipping hammers to each other.

Feed force in the standardized chipping hammer test is defined as the downward push force acting on the tool handle, which is in addition to the weight of the power tool itself (ISO 8662-2). The results of the present study clearly demonstrate that the feed force is an influential factor affecting the vibration emission of the chipping hammer operating on the energy absorber. Therefore, an appropriate selection of feed forces to be used during testing is critical in making a fair judgment of chipping hammer vibration performance. In reality, a great range of feed forces may be applied to chipping hammers in the field, depending on user preferences, the accuracy of the position control required in a task and the materials being worked on. The feed forces actually used in the field have not been well studied. It may be difficult to determine a single representative feed force for standardized testing. The current standard test method specifies that the feed force (in N) shall be equal to 40 times the tool mass in kilograms, provided that the feed force shall be not less than 80 N and not more than 200 N (note that there is a misprint in the current ISO 8662-2 standard document: 40 times the tool mass is specified for the feed force calculation but the value used in the example described in the document is 30 times). The results of the present study suggest that this standardized feed force determination method may present several problems.

According to the standard feed force determination method, the feed force for the two chipping hammers (6.6 and 6.9 kg without the chisel bit, respectively) used in the present study should be ~200 N (use either 30 or 40 times the tool mass). A very poor repeatability of the test data was observed at this high feed force, as suggested by the CV values presented in Table 6. The large variation at the high feed force may be the result of the high sensitivity of the tool–absorber interaction to the orientation and the accuracy of the applied feed force. More critically, the magnitudes of the weighted accelerations at

200 N were significantly lower than those at the other two feed forces. These tools would be classified as highly recommended tools if the vibration emission data obtained at the 200 N feed force were to be used for the judgment. However, they could generate much larger vibration emission at workplaces when used at other feed force levels. Therefore, it may not be appropriate to assess the tools based on the data obtained under such a single high feed force.

In actual tool operation in the field, the applied feed force on the tool handle may not really increase with the tool weight. Instead, feed force may actually decrease with heavier tools as the operator uses the additional tool weight to assist in the tool operation. This contradicts the ISO assumption of a proportional relationship between tool weight and feed force. It may be more reasonable to define the feed force as the load applied to the chisel end or by modifying the standard method to better represent the relationship, if any, between feed force and tool weight. It may be argued that the major objective of the feed force applied in the test is to maintain good control of the chipping hammer operation, not to simulate the working condition. The results and the observations made during this study suggest that the chipping hammers can be well controlled at the low feed forces and that the relationship between the tool weight and feed force is not necessarily proportional.

The two chipping hammers used in this experiment have similar weights and capacities. One of the tools (Tool A) consistently generated less vibration than the other tool at every force level. Thus, for tool screening purposes, only one force level would have been necessary to rank these two tools. However, it is unknown whether tools with different capacities and weights would behave differently at different feed forces. In order to compare tools with differing weights and capacities, an experiment using multiple feed forces may provide more information for a better comparison of the tool vibration behaviors.

The statistical results suggest that the tool vibration values obtained from different subjects were significantly different. Therefore, the inter-subject differences may be one of the factors that could explain the variations between the data obtained from different laboratories. The mechanical impedances of the subjects may influence the tool behaviors (ISO 10068; ISO, 1998). However, there was generally no reliable correlation between the subject's anthropometrics and the vibration emissions of the two chipping hammers that were used in this study. The differences between subtle posture differences along with possible variability in the subject's ability to accurately control the feed force might contribute to the variation of the chipping hammer vibration emissions.

In addition to the effects of the subjects, the difference between energy absorbers and the chisels used in different laboratories may also lead to the reported variations in measured vibration emissions (Schenk and Gillmeister, 1998). The energy dissipation process over successive uses may eventually change the chisel characteristics and the damping and stiffness characteristics of the energy absorber. Over time, rust and other aging effects on the steel balls and other components may also alter the absorber's properties. These factors may cause some inter- and intra-laboratory test discrepancies. For tool comparison experiments, efforts to minimize errors caused by use and aging effects might include the use of a well-maintained reference tool and the maintenance and/or replacement of the steel balls used in the energy absorber. It is anticipated that deterioration of the chipping hammer would be slower than that of the energy absorber. Because changes in the energy absorber and anvil-headed chisel may occur with use, a random test procedure similar to that employed in the present study should be used during tool comparison experiments to statistically counter the impact of this possibility. The relative difference or the percentage difference between the reference tool and the tested tool should be used to judge the vibration performance of the tested tool.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results and observations made in the present study, several conclusions and recommendations are made as follows.

Chipping hammer vibration emissions generated on the energy absorber vary by subject. However, the intra- and inter-subject variations appear to be practically acceptable over a certain range of feed force.

The applied feed force strongly affects the vibration emission of the chipping hammers operating on the ISO energy absorber. The peak value of the tool vibration at the tool dominant frequency (air blow rate) generally decreases with an increase in feed force, but high frequency vibration components (say >100 Hz) generally increase with an increase in feed force, which results in an increase in the unweighted accelerations with an increase in feed force. Conversely, the ISO weighted accelerations decrease with an increase in feed force.

The energy absorber at the high feed force (200 N) did not provide a stable feedback and the vibration emission is not reasonably repeatable. This situation suggests a need to employ a lower value as the upper limit to the range of feed forces used in the application of the ISO-8662-2 standard, if the tool could not generate repeatable vibration emission.

Because chipping hammers are actually operated with a wide range of feed forces and the vibration emission associated with the energy absorber is affected by the feed force, the results obtained at a single feed force may not be sufficient to represent the tool behaviors. It is thus recommended to use multiple levels of feed force in an appropriate range for chipping hammer testing. Doing so may provide a more appropriate basis for tool screening.

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